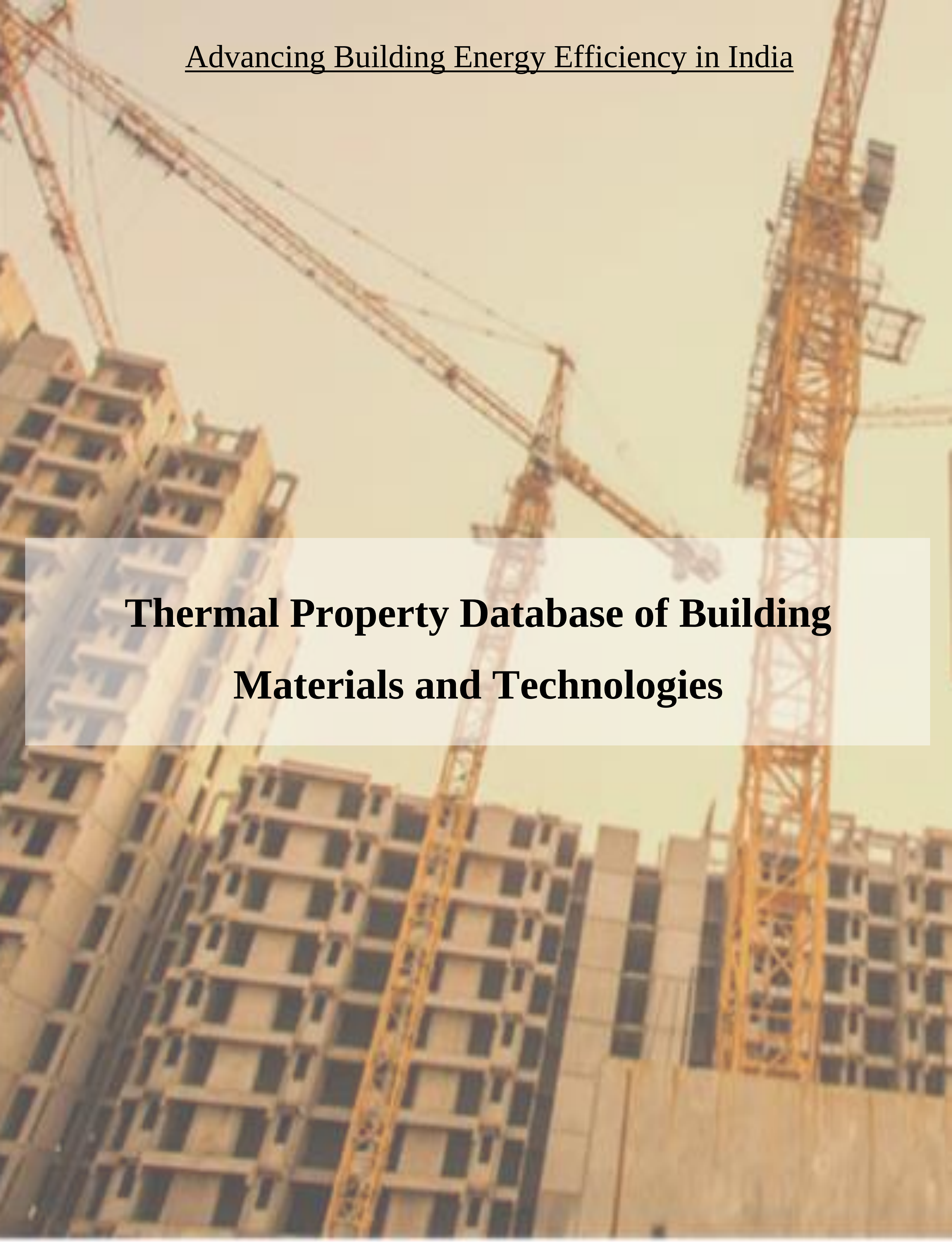
Advancing Building Energy Efficiency in India

Thermal Properties Database of Building Materials and Technologies

SHAKTI SUSTAINABLE ENERGY FOUNDATION

CRDF CEPT RESEARCH AND DEVELOPMENT FOUNDATION

CARBSE CENTER FOR ADVANCED RESEARCH IN BUILDING SCIENCE AND ENERGY



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Executive Summary

This executive summary outlines the findings and implications of a comprehensive report conducted by the CEPT Research and Development Foundation (CRDF) at CEPT University. The primary objective of this report is to enhance understanding of thermal performance evaluation in walling materials, walling technologies and roofing construction technologies. Walling materials have been tested for their thermal conductivity, bulk density, water absorption, compressive strength and specific heat capacity while thermal transmittance (U-values) have been calculated for Walling technologies and roofing technologies.

Research Objective: The report focuses on providing the thermal performance of various construction technologies, essential for sustainable building practices.
State-of-the-Art Facilities: Thermal transmittance (U- value) derivation happens through a rigorous testing conducted in the state of the art, Guarded Hot Box (GHB).

Implications and Recommendations:
Better Decision Making: The insights provided in this report will contribute to a deeper understanding of thermal dynamics in building structures, thereby informing more informed decision-making in construction and design.
Promoting Sustainability: By providing reliable data on the thermal performance of roof construction technologies, this report supports the adoption of sustainable building practices, ultimately leading to energy efficiency in the buildings and environmental conservation.

There are four parts of the book:

- **Part I: National Database of Thermophysical Properties of Walling Materials**
  This project report contains the following:

1. Database of the thermophysical properties of sixty-two samples of solid masonry building units from various Indian states/climatic zones. The properties measured for each sample are dry density, thermal conductivity, volumetric specific heat, water absorption, and compressive strength.
2. An approximate of the correlation between dry density and thermal conductivity of the solid masonry building materials.
3. Calculation of thermal transmittance (U-value) and Residential Envelope Transmittance Value (RETV) of the building envelope from selected housing designs through the measured thermal conductivity values

- **Part II: Derivation of U-values of Wall Assemblies and Walling Technologies**
  This research activity tests thirty-four wall assemblies for their thermal transmittance values that may fall in one of the following categories:

1. Conventional Walling Technologies: This includes business-as-usual wall assemblies such as burnt clay brick, RCC walls, etc can be used as reference baselines.
2. Alternative Walling Technologies: This category includes region-specific walling assemblies used in vernacular architecture such as bamboo-Crete, rammed earth walls, etc
3. Emerging Walling Technologies: This category refers to industrialized walling technologies, systems, and/ or products such as reinforced EPS core panel systems.

- **Part III: Derivation of U-values of Roofing Technologies**
  This research activity tests ten roofing assemblies for their thermal transmittance value that may fall in one of the following categories:
1. Conventional Roofing Technologies: This includes business-as-usual roof assemblies such as RCC slabs, Precast Hollow core slab, decking slab etc. that can be used as reference baselines.
2. Alternative Roofing Technologies: This category includes region-specific roofing assemblies used in vernacular architecture such as various kinds of Mangalore tiled roofs, thatch roofs etc.
3. Emerging Roofing Technologies: This category refers to industrialized roofing technologies, systems, and/ or products such as Tepper quad bubble deck, Light weight steel gauge roofing etc.

- **Part IV: Thermo-physical properties of Building Materials**

This project report contains the following:

1. Density, Thermal conductivity and specific heat of various building materials including various kinds of bricks, cement and asbestos boards, plaster, stones and glass.

Table 1: Thermal transmittance value database of all walling assemblies and technologies

S. No.	Wall types	Thickness (mm)	U value (W/m^{2}K)
Phase- I			
1	Rattrap bond wall	250	2.11
2	Light Gauge framed steel structure with EPS	136	1.37
3	Light Gauge framed steel structure with PPGI Sheet	150	2.12
4	Reinforced EPS core Panel system	150	0.56
5	Glass fibre reinforced Gypsum Panel - Unfilled	124	2.06
6	Glass fibre reinforced Gypsum Panel - with RCC & non-structural filling	124	2.12
7	Glass fibre reinforced Gypsum Panel - with partial RCC filling	124	2.13
8	Brick Wall	250	2.41
9	Structural stay-in-place formwork system (Coffer) – Insulated panel	230	0.44
Phase- II			
10	Bamboo Crete	65	2.71
11	Wattle and Daub	45	3.61
12	Stabilized Adobe	230	2.11
13	Laterite Block Wall	205	2.17
14	Unstabilized Adobe	230	2.05
15	Compressed Stabilized Earth Block wall (CSEB)	230	2.79
16	Unstabilized Compressed Earth Block Wall	230	2.74
17	AAC Block Wall with Perlite-based Cement Plaster	230	0.76
18	Unstabilized Rammed Earth	230	2.13

19	Stabilized Rammed Earth	230	2.09
20	AAC Block Wall with Cement Mortar and Cement Plaster	230	0.78
21	AAC Block Wall with Lime mortar and Lime Plaster	220	0.82
22	Burnt Clay Brick with Lime Mortar and Lime Plaster	250	2.31
23	Limestone with Lime Mortar and Lime Plaster	224	2.84
24	Limestone with Cement Mortar and Cement Plaster	230	2.82
Phase-III			
25	Hollow Clay Brick (100mm thick) with Cement Plaster	130	2.71
26	Hollow Clay Brick (100mm thick) with Cement Plaster and XPS	158	0.89
27	Hollow Clay Brick (200mm thick) with Rockwool and Cement Plaster	230	1.28
28	Hollow Clay Brick (200mm thick) with Cement Plaster	230	1.83
29	Hollow Clay Brick (200mm thick) with Cement Plaster and XPS	258	0.75
30	RCC Wall (100 mm thick)	100	3.59
31	RCC Wall with EPS	153	0.58
32	RCC Wall with Styrofoam on both sides	154	0.65
33	RCC Wall with PVC panels on both sides	112	2.62
34	RCC Wall with PVC panels on both side and EPS board	165	0.52

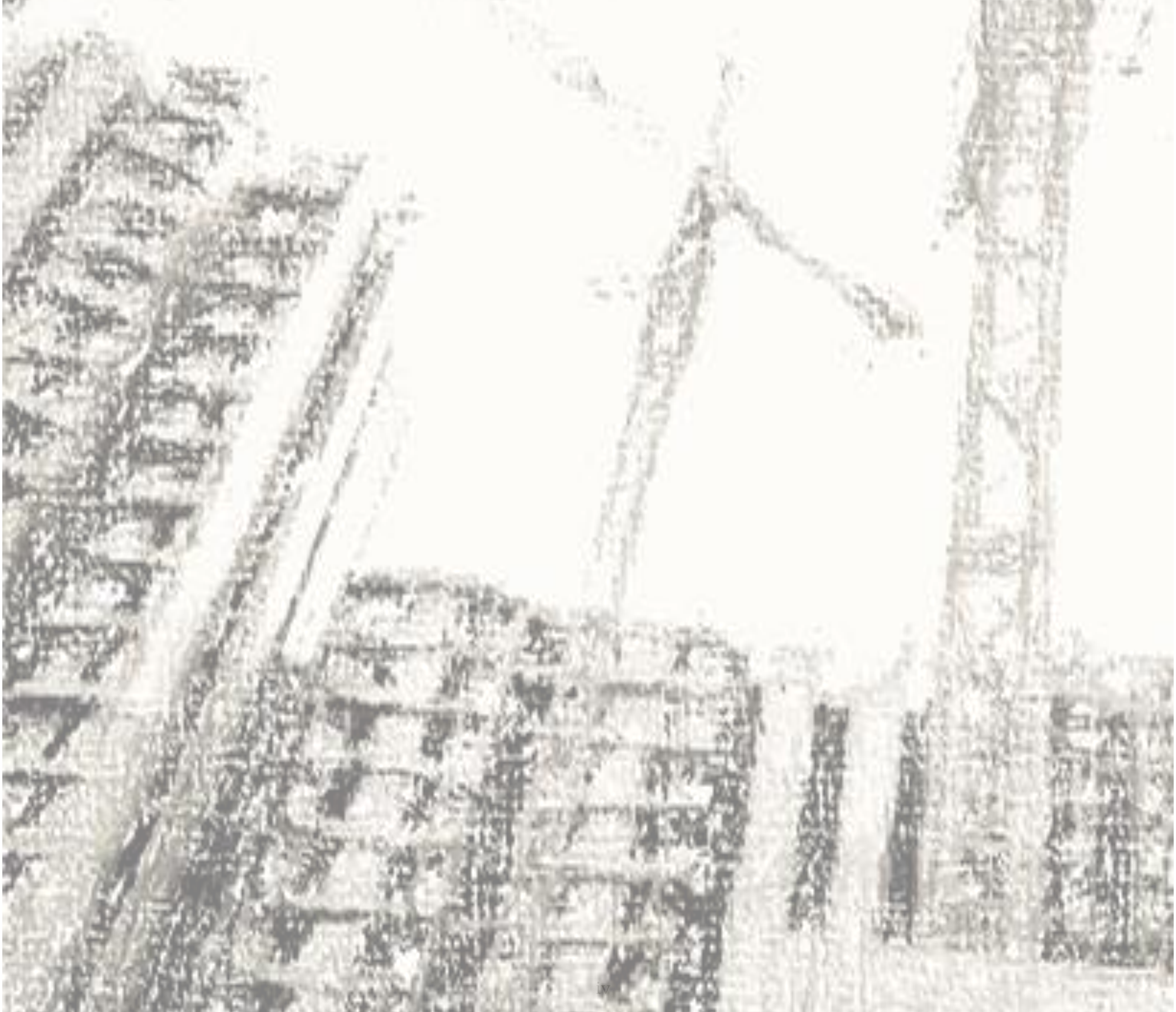
Table 2: Thermal transmittance value database of all roofing assemblies and technologies.

S/N	Roof Types	Thickness (mm)	U-value (W/m^2K)
1	Flat PUF-insulated roof panels with PPGI sheet	121.4	0.253
2	Curved PUF-insulated roof panels with PPGI sheet	121.4	0.246
3	TRIMDEK Profile with PUF insulation and Aluminum sheet waterproofing	76.2	0.255
4	Timber + Single sided Mangalore tile roofing	93.0	1.505
5	Timber + Double sided Mangalore tile roofing	105.0	1.117
6	Bamboo + Single sided Mangalore tile roofing	108.0	1.502
7	Bamboo + Double sided Mangalore tile roofing	114.0	1.122
8	Thatch roof	246.0	0.234
9	Thatch roof + XPS insulation	321.0	0.177
10	Timber + Single sided Mangalore tile roofing + Cement Fiber Board	105.0	1.484

Advancing Building Energy Efficiency in India

Thermal Performance of Walling Material and Wall Technology

Part I: National Database of Thermophysical Properties of Walling Materials



October 2022

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Advancing Building Energy Efficiency in India

Thermal performance of Walling Materials and Wall Technology

Part 1: National Database of Thermophysical Properties of Walling Materials

October 2022

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1. Introduction

Buildings consume a significant amount of energy, thus contributing to climate change. According to *Energy Statistics* (2017) published by the Ministry of Statistics, Planning and Implementation, the building sector consisting of residential and commercial buildings, consumed nearly a third of the total electricity produced in the year 2016. The policy think tank of the Government of India, *Niti Aayog*, estimated that electricity demand from the building sector will increase by more than 800% in 2047 compared to 2012 (Sumedha Malaviya & Jairaj, 2017). The forecasted increase in electricity demand by buildings is primarily attributed to the increase in built-up areas and increased use of electricity for space cooling. As the major chunk of the country's electricity generation is still being met by burning fossil fuels, this surge in electricity demand would be detrimental to the environment.

To reduce energy consumption in buildings, the Energy Conservation Building Code (ECBC), was developed and launched by the Ministry of Power (MoP) and the Bureau of Energy Efficiency (BEE), Government of India, in May 2007, to set the minimum requirement of energy efficiency for new, large commercial buildings. A revised version of ECBC was released in 2017 and in 2018, Ministry of Power (MoP) launched Eco- Niwas Samhita (ENS), which is the Energy Conservation Building Code for residential buildings. The objective behind implementing these codes is to reduce energy consumption in newly constructed commercial and residential buildings.

Heat transmission from a building envelope (external walls, windows and roof) constitutes a large part of the heat gain in a building. Both ECBC and ENS aim at reducing the heat transmission from the building envelope. ENS defines Residential Envelope Transmittance Value (RETV) as the parameter which accounts for heat conduction through external walls/windows and solar heat transmission through window glazing. ENS specifies a maximum value of ($15\ \mathrm{W/m^2}$) for meeting the RETV criterion. To a great extent, RETV is dictated by the thermal conductivity value of an external wall. A majority of the external wall construction in India is masonry construction using solid bricks and blocks. Thus, exhaustive data of the thermal and physical properties of a wide range of walling bricks and blocks is of paramount importance in calculating RETV and in the effective implementation of ENS, across different climatic zones in India.

Thermophysical properties mentioned in the building codes and website of BEE are 'typical values' only for a few types of walling materials. Since a wide variety of masonry bricks and blocks is used in the construction of buildings across the country, showing a large variation in thermophysical properties, it is imperative to develop a database which can be used for accurate estimation of RETV for the implementation of ENS and for simulating energy performance of any new or existing building.

To develop such a database a joint project (conducted by GKSPL and CEPT University) was initiated to collect and test samples of commonly used walling materials. The aim of this project is to build a nation-wide database of thermophysical properties of a wide range of walling materials used for construction viz., solid fired clay brick, fly ash brick, concrete block, autoclaved aerated concrete (AAC) block, cellular light weight concrete (CLC) block and compressed stabilized earth block (CSEB). Only solid (without any perforations) units that can be measured using uniform protocol have been considered in this project. Perforated building units require special measurement protocol. This project report contains the following:

1. Database of the thermophysical properties of sixty-two samples of solid masonry building units from various Indian states/climatic zones. The properties measured for each sample are dry density, thermal conductivity, volumetric specific heat, water absorption, and compressive strength.
2. An approximate of the correlation between dry density and thermal conductivity of the solid masonry building materials.
3. Calculation of thermal transmittance (U-value) and Residential Envelope Transmittance Value (RETV) of the building envelope from selected housing designs through the measured thermal conductivity values.

1.1 Literature Review

Buildings in most parts of India are designed to keep heat out for the greater part of the year. However, this undesirable heat gets transferred inside the building mainly from conduction through the walls and the roofs. Thermal conductivity (λ) is the key physical property of building materials that characterizes the resistance (thermal insulation) to the passage of heat. The factors that affect effective thermal conductivity of solid building bricks and blocks can be classified as: (i) macroscopic structure i.e., presence of cavities and their configuration, (ii) mineralogical composition and (iii) microstructure (Gualtieri et al., 2010). In case of fired clay bricks, earlier studies pointed out that thermal conductivity of bricks is mainly dependent on their dry density but, new studies (Gualtieri et al., 2010) and (Dondi et al., 2004) argued that other than dry density, mineralogical composition, organic content, size and size distribution of pores, and grain size distribution also played a key role in determining the insulating properties of bricks. Some trends or correlations regarding the relationship among thermal conductivity and aforementioned factors were presented through a statistical treatment of data; but a conclusive model could not be built due to the complexity of the system and the limited amount of data.

Although the thermal insulation property of a building material strictly depends on many factors, this project aims at finding a suitable correlation between dry density and thermal conductivity values of common building materials produced in India. It is intended that the proposed correlation will provide a priori better estimate of thermal conductivity using the corresponding dry density (easily measurable) value of a given solid masonry unit.

Inside surface temperatures of walls, floors and roofs of a building envelope need to be estimated in order to quantify thermal conform. If boundary conditions (temperature and heat flow rate at exposed surfaces) are not changing with time, a technique of steady state, based on the calculation of the thermal transmittance (*U*-value) of the building walls, is used to evaluate the inside surface temperatures. For one-dimensional steady state conduction, the overall thermal transmittance or *U*-value ($\mathrm{Wm^{-2}K^{-1}}$) of a wall composed of plane homogenous isotropic layers of materials is given as:

$$U = \frac{1}{\sum_{i=1}^{N} \frac{x_i}{\lambda_i} + R_{si} + R_{so} + R_c} \qquad \dots (1.1)$$

Where N is the number of layers in the construction, x_i (m) the thickness of layer i, λ_i ($\mathrm{Wm^{-1}K^{-1}}$) the thermal conductivity of layer i, R ($\mathrm{m^2KW^{-1}}$) is the combined radiative and convective thermal resistance, and subscript *si*, *so*, and *c* refer to the innermost surface, outermost surface and cavity respectively. This equation shows that under steady state conditions, assessment of thermal performance of the wall (or thermal comfort of the interior space) is done through an evaluation of its effective resistance to heat transfer alone.

To understand this assessment, Table 1 gives representative values of thermal parameters for some common solids used in buildings (Davies, 2004).

Table 1: Representative thermal parameters of some common solids

	Thermal conductivity λ $(\mathrm{W/m.K})$	**Dry density** ρ $(\mathrm{kg/m^3})$	**Specific heat** C_p $(\mathrm{J/kg.K})$	**Diffusivity** $\alpha \times 10^6$ $(\mathrm{m^2/s})$	**Effusivity** ϵ $(\mathrm{Ws^{0.5}/m^2.K})$
Solid glass	1.05	2500	840	0.50	1485
Steel	45	7800	480	12.02	12980
Polyurethane foam	0.028	30	1470	0.63	35
Mineral fibreboard	0.042	240	760	0.23	88
Cement fibreboard	0.082	350	1300	0.18	193
Lightweight masonry	0.22	570	840	0.46	324
Heavyweight masonry	0.90	1850	840	0.58	1183

Common earth	1.28	1460	880	1.00	1282
Cement mortar, dry	0.93	1900	840	0.58	1218
Lightweight concrete block	0.73	1800	840	0.48	1051
Heavyweight concrete block	1.31	2240	840	0.70	1570
Dry ceramic tiles	1.20	2000	850	0.71	1428

1.2 Report layout

This report consists of four chapters. Chapter 2 contains information on materials selected for measurements and their tested properties. Chapter 3 gives material wise test results and the various data plots that were measured. Chapter 4 includes RETV calculation for a sample affordable housing scheme. Annexure I contains definitions of the various terms used in the report and nomenclature. Annexure II provides explanations of the various methodologies used for the measurement of properties. Annexure III provides the datasheets for all the materials that were tested

2. Materials and Measuement methods

In India several types of building masonry units are used for construction, predominantly solid bricks and blocks. At present, 80% of all bricks produced in India are fired clay bricks. In terms of the production of solid fired clay bricks, India can be broadly divided into two regions – (a) Indo-Gangetic plain and (b) Peninsular and coastal India. Indo-Gangetic plains accounts for about 70% of total brick production. Major brick producing states in this region are Punjab, Haryana, Uttar Pradesh, Bihar and West Bengal. Rest of the 30% of bricks are produced in peninsular and coastal region of India in which states of Gujarat, Maharashtra, Madhya Pradesh, Odisha, and Tamil Nadu are the main contributors.

In both these regions, the majority of clay bricks are still made manually and are fired in the conventional Bull's Trench Kilns and Clamps. A very small proportion of fired clay bricks are made in semi or fully-mechanized brick plants. Most of the mechanization in the Indian brick industry is found only in the processes leading to the production of green bricks; i.e. clay extraction, mixing of clay and moulding of bricks. Barring a handful of plants that use modern tunnel kilns, most mechanized plants are still using traditional kilns for firing bricks. Solid fired clay bricks produced from mechanized plants are denser and have higher compressive strength as compared to the hand moulded bricks.

The use of fly ash (a by-product of coal combustion) brick as an alternative to fired clay bricks in building construction is also slowly gaining steam in India. Yet, these bricks are mostly being used in construction activities in the urban areas. Fly ash bricks are made in mechanized plants where pan-mixer is used to mix fly ash with sand, stone-dust, lime and cement to prepare the required blend of mixture. Bricks are shaped out of this mixture using a vibro-hydraulic power compacting machine and are cured with water to attain the required strength.

Other less common types of solid bricks or blocks used in construction include solid concrete, calcium silicate, autoclaved aerated concrete, compressed stabilized earth block, etc. Similar to fly ash bricks, these alternative building units are also produced in semi-mechanized or mechanized plants where a particular proportion of raw materials is mixed together using a mixer, and bricks or blocks are moulded using the resultant mixture.

It was decided therefore to collect samples of building materials from different parts of the country in order to encompass the effect of diverse material composition and manufacturing processes on material properties.

2.1 Sample Collection

The types of solid bricks/blocks selected for measuring thermophysical properties are as follows:

1. Fired clay brick
2. Fly ash brick
3. Solid concrete brick
4. Solid concrete block
5. Calcium silicate block
6. Autoclaved aerated concrete block (AAC)
7. Cellular light weight concrete block (CLC)
8. Compressed stabilized earth block (CSEB)
9. Demolition waste brick
10. Expanded clay aggregate
11. Surkhi brick

A total of sixty-two samples were collected from thirteen different states of India to represent the wide range of solid masonry building units used in construction. Individual datasheets containing information about the collection site and manufacturing processes are given in the annexure. Table 2 shows the details of state-wise distribution of samples collected for measurements and Figure 1 shows their location on the map.

Table 2: State-wise distribution of samples collected.

	Fired clay Brick	Fly ash Brick	Concrete Brick	Solid Concrete Block	Calcium Silicate Block	AAC	CLC	CSEB	Demolition waste brick	Expanded clay aggregate	Surkhi brick
Tamil Nadu	4	1	-	-	-	-	-	1	-	-	-
Telangana	1	1	-	1	-	-	-	-	-	-	-
Andhra Pradesh	3	1	-	2	-	-	1	-	-	-	-
Maharashtra	2	2	-	-	1	1	1	-	-	-	-
Gujarat	2	2	-	1	-	-	1	-	1	1	1
Bihar	1	1	-	-	-	-	-	-	-	-	-
Delhi & NCT	1	1	-	-	-	-	-	1	-	-	-
Uttar Pradesh	3	-	-	-	-	-	-	-	-	-	-
Madhya Pradesh	1	1	-	-	-	-	-	-	-	-	-
West Bengal	1	1	-	-	-	-	-	-	-	-	-
Haryana	3	1	-	-	-	1	-	-	-	-	-
Karnataka	2	-	-	1	-	-	-	1	-	-	-
Punjab	2	1	1	-	-	-	-	-	-	-	-
Rajasthan	-	5	-	-	-	-	-	-	-	-	-
Total	**26**	**18**	**1**	**5**	**1**	**2**	**3**	**3**	**1**	**1**	**1**

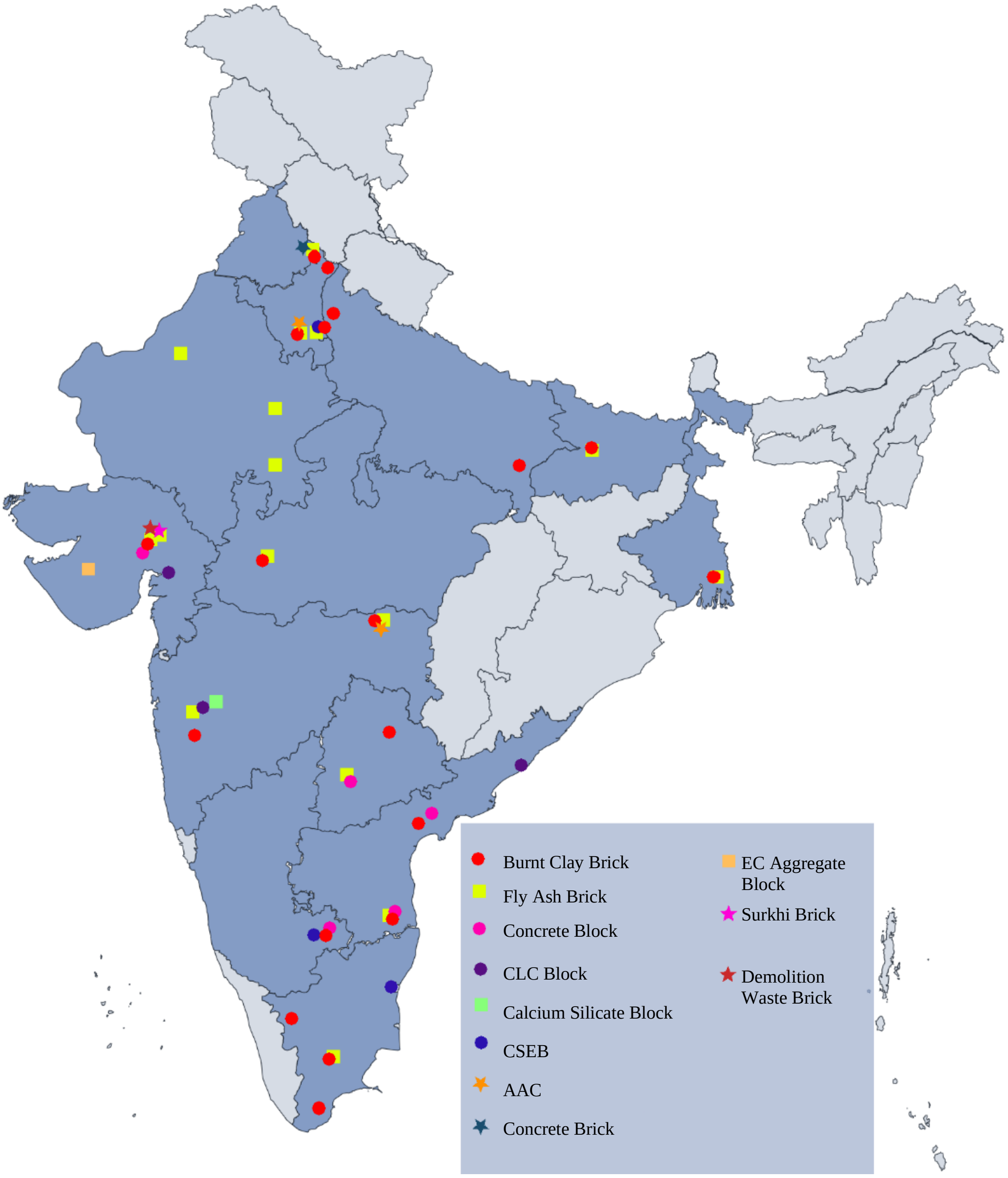


Figure 1: Location of all samples collected

2.2 Measurement of Properties

All material samples delivered to CARBSE, CEPT University were checked and tagged before testing as explained in Annexure II. Each of the sixty-two sample sets consisting of both bricks and blocks were characterised by the following properties:

1. Thermal conductivity
2. Specific heat
3. Dry density
4. Water absorption
5. Compressive strength.

Annexure I provides definitions of all the tested parameters. Table 3 describes the instruments used and applicable testing standards followed by CARBSE for testing each parameter. Thermal conductivity and specific heat were measured using Thermal Constants analyser as per ISO/DIS 22007-2:2015 as seen in Table 3. Similarly, dry density, water absorption, and compressive strength were measured following specific standards of measurement as seen in Table 3. The testing procedure specifying environmental conditions and sample requirements for each parameter is elaborated along with photographs of the samples in Annexure II.

Table 3: Measured properties and corresponding testing standards & instruments used

S/N	Testing parameter	Instrument	Applicable Testing Standard
1	Thermal Conductivity and Specific heat	Thermal Constants Analyser	ISO/DIS 22007-2:2015 (for both bricks and blocks) (ISO, 2008)
2	Dry density	Precision Weighing Scale, Inert Gas Oven, Water Bath	ASTM C20 (for both bricks and blocks) (ASTM, 2015)
3	Water Absorption	Precision Weighing Scale, Inert Gas Oven, Water Bath	IS 3495 (for bricks) (BIS, 1992b) IS 2185 (for blocks) (BIS, 2005)
4	Compressive Strength	Compression Testing Machine	IS 3495 (for bricks) IS 2185 (for blocks)

3. Results and Discussion

The annexure III contains individual datasheets with the measured thermophysical properties of all the sixty-two samples. The number of samples collected are sufficient to statistically determine a correlation between any two parameters. Only fired clay bricks and non-fired or cured bricks are considered for examining the influence of dry density on thermal conductivity.

3.1 Fired Clay Bricks

Table 4 shows the manufacturing process and location and Table 5 shows average value of measured properties of the fired clay brick samples tested, categorised by the manufacturing process.

Table 4: Location and manufacturing process of fired clay samples selected.

Phase	S/N	Sample	Manufacturing Process (Moulding)	Location
I	1	RB01	Hand-moulding	Kolkata, West Bengal
	2	RB02	Hand-moulding	Jhajjar, Haryana
	3	RB03	Extrusion	Jhajjar, Haryana
	4	RB04	Hand-moulding	Patna, Bihar
	5	RB05	Extrusion	Dera Bassi (Mohali), Punjab
	6	RB06	Hand-moulding	Dera Bassi (Mohali), Punjab
	7	RB07	Hand-moulding	Moraiya (Ahmedabad), Gujarat
	8	RB08	Water-struck moulding	Moraiya (Ahmedabad), Gujarat
	9	RB09	Hand-moulding	Bhor (Pune), Maharashtra
	10	RB10	Hand-moulding	Indore, Madhya Pradesh
	11	RB11	Hand-moulding	Nagpur, Maharashtra
	12	RB12	Extrusion	Anekkal (Bengaluru), Karnataka
	13	RB13	Soft mud moulding	Anekkal (Bengaluru), Karnataka
	14	RB14	Hand-moulding	Guntur, Andhra Pradesh
	15	RB15	Hand-moulding	Karimnagar, Telangana
	16	RB16	Soft mud moulding	Tirunelveli, Tamil Nadu
	17	RB17	Soft mud moulding	Madurai, Tamil Nadu
	18	RB18	Extrusion	Madurai, Tamil Nadu
	19	RB19	Extrusion	Chinnathadagam (Coimbatore), Tamil Nadu
	20	RB20	Hand-moulding	Yamunanagar, Haryana
	21	RB21	Hand-moulding	Baraut (Baghpat), Uttar Pradesh
	22	RB22	Soft mud moulding	Varanasi, Uttar Pradesh
	23	RB23	Hand-moulding	Varanasi, Uttar Pradesh
II	24	RB01	Hand-moulding	Baghpat, Delhi-NCR
	25	RB02	Soft mud moulding	Tirupati, Andhra Pradesh
	26	RB03	Hand-moulding	Tirupati, Andhra Pradesh

Table 5: Average value of measured properties of fired clay samples selected.

S/N	Phase	Sample	Dry density ρ (kg/m^3)	Thermal conductivity λ $(W/m.K)$	Specific heat C_p $(J/kg.K)$	Compressive strength (MPa)	Water absorption (%)
				Hand-Moulding			
1	Phase I	RB01	1599	0.48	907.8	14.83	21
2	Phase I	RB02	1777	0.60	921.6	16.54	15
3	Phase I	RB04	1654	0.57	917.5	23.08	19
4	Phase I	RB06	1887	0.76	927.0	20.23	12
5	Phase I	RB07	1738	0.53	960.4	7.21	16
6	Phase I	RB09	1604	0.39	909.0	6.10	23
7	Phase I	RB10	1512	0.42	926.5	5.32	26
8	Phase I	RB11	1447	0.50	936.6	10.01	24
9	Phase I	RB14	1503	0.42	935.9	4.88	26
10	Phase I	RB15	1264	0.38	927.8	4.16	32
11	Phase I	RB20	1780	0.55	952.9	18.68	15
12	Phase I	RB21	1716	0.54	923.1	17.8	17
13	Phase I	RB23	1819	0.74	978.6	25.8	13
14	Phase II	RB01	1801	0.57	926.9	21.76	12
15	Phase II	RB03	1493	0.41	909.6	5.22	20
				Extrusion			
1	Phase I	RB03	2119	0.97	916.1	58.21	7
2	Phase I	RB05	2028	1.12	955.2	54	10
3	Phase I	RB12	1975	0.80	928.1	26.83	12
4	Phase I	RB18	1895	0.58	924.3	19.82	14
5	Phase I	RB19	1958	0.65	947.2	10.79	13
				Soft mud Moulding			
1	Phase I	RB13	1807	0.59	934.8	13.48	17
2	Phase I	RB16	1657	0.42	940.4	7.51	19
3	Phase I	RB17	1648	0.41	927.5	5.71	20
4	Phase I	RB22	1798	0.64	918.5	26.17	14
5	Phase II	RB02	1723	0.58	891.1	5.84	12
				Water-struck Moulding			
1	Phase I	RB08	1737	0.51	946.8	7.76	16

Analysis of the data presented in Table 5 shows that the dry density and thermal conductivity of hand-moulded bricks -show a wide range from $1264 - 1887\ \mathrm{kg/m^3}$ and $0.38 - 0.76\ \mathrm{W/m.K}$ respectively, whereas the dry density and thermal conductivity for machine moulded (extruded or soft-mud moulded) bricks varies between $1648 - 2119\ \mathrm{kg/m^3}$ and $0.41 - 1.12\ \mathrm{W/m.K}$ respectively.

Figure 2 shows the variation of thermal conductivity with dry density for fired clay bricks. Using Microsoft Excel, an exponential correlation is fit to the data. Goodness of fit ($R^2 = 0.70$) shows that dry density is a major factor that governs thermal conductivity of solid fired clay bricks. Thus, for a given value of dry density ρ ($\mathrm{kg/m^3}$), the following equation can be used to make an estimation of thermal conductivity λ ($\mathrm{W/m.K}$) for fired clay bricks:

$$\lambda = 0.0652e^{(0.0012\rho)} \qquad (1250 < \rho < 2150) \qquad \text{... (3.1)}$$

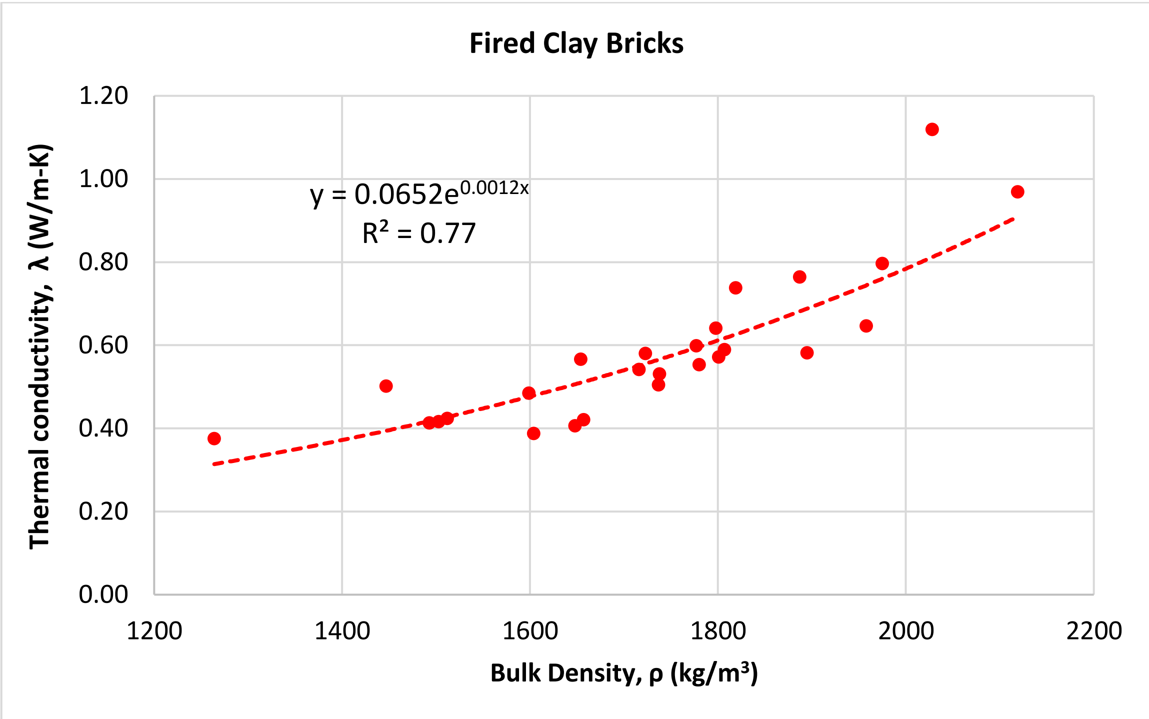


Figure 2: Thermal conductivity as a function of dry density for fired-clay bricks

3.2 Non-Fired (Cured) Bricks

Table 6 shows the source location and Table 7 shows the average value of measured properties of the tested fly ash brick samples.

Table 6: Source location of the flyash brick samples

	S.No	Sample	Location
Phase I	1	FB01	Kolkata, West Bengal
	2	FB02	Jhajjar, Haryana
	3	FB03	Patna, Bihar
	4	FB04	Najafgarh, NCT
	5	FB05	Chandigarh, Punjab
	6	FB06	Ahmedabad, Gujrat
	7	FB07	Pune, Maharashtra
	8	FB08	Indore, Madhya Pradesh
	9	FB09	Nagpur, Maharashtra
	10	FB10	Madurai, Tamil Nadu
Phase II	11	FB01	Hyderabad, Telangana
	12	FB02	Tirupati, Andhra Pradesh
	13	FB03	Ahmedabad, Gujarat
	14	FB04	Kota, Rajasthan
	15	FB05	Kota, Rajasthan
	16	FB06	Jaipur, Rajasthan
	17	FB07	Jaipur, Rajasthan
	18	FB08	Bikaner, Rajasthan

Table 7: Average value of measured properties of flyash brick samples

	S.No	Sample	Bulk Density ρ (kg/m^3)	Thermal conductivity λ $(W/m.K)$	Specific heat C_p $(J/kg.K)$	Compressive strength (MPa)	Water absorption (%)
Phase I	1	FB01	1878	0.86	938.2	19.98	12
	2	FB02	1844	0.80	924.8	12.43	16
	3	FB03	1475	0.53	962.0	9.02	23
	4	FB04	1299	0.39	924.0	11.44	27
	5	FB05	1807	0.50	961.5	10.64	15
	6	FB06	1543	0.36	908.0	5.05	27
	7	FB07	2048	0.67	976.2	15.16	12
	8	FB08	1682	0.52	936.0	10.14	19
	9	FB09	1989	0.65	929.9	8.87	13
	10	FB10	1722	0.50	925.6	3.6	20
Phase II	11	FB01	1878	1.05	918.05	15.72	10
	12	FB02	1779	0.84	935.35	18.72	15
	13	FB03	1716	0.56	891.33	12.07	17
	14	FB04	1606	0.67	953.90	9.97	19
	15	FB05	1627	0.69	954.46	8.57	18
	16	FB06	1774	0.97	878.71	10.33	15
	17	FB07	1734	0.79	972.16	8.75	18
	18	FB08	1694	0.75	646.16	15.16	20

The bulk density and the thermal conductivity of fly ash bricks show a wide range, ranging from $1299 - 2048\ \mathrm{kg/m^3}$ and $0.36 - 0.97\ \mathrm{W/m.K}$, respectively. Table 8 shows the sample type and location and Table 9 shows average value of measured properties of other non-fired walling material samples tested.

Table 8: Source location of other non-fired walling material samples

	S.No	Sample	Sample type	Location
Phase I	1	AB01	AAC Block	Nagpur, Maharashtra
	2	AB02	AAC Block	Jhajjar, Haryana
	3	EB01	CSEB	New Delhi, NCT
	4	EB02	CSEB	Kengeri (Bengaluru), Karnataka
	5	CC01	Concrete Block	Bengaluru, Karnataka
	6	CC02	Concrete Block	Vijayawada, Andhra Pradesh
	7	CB01	Concrete Brick	Mohali, Punjab
	8	CS01	Calcium Silicate block	Vadhu Budruk (Pune), Maharashtra
	9	CL01	CLC blocks	Kesnand (Pune), Maharashtra
Phase II	1	CC01	Concrete Block	Adibutla, Hyderabad, Telangana
	2	CC02	Concrete Block	Tirupati, Andhra Pradesh
	3	CC03	Concrete Block	Bagodara, Gujarat
	4	CL01	Cellular Light Weight Concrete (CLC) Block	Vishakhapatnam, Andhra Pradesh
	5	CL02	Cellular Light Weight Concrete (CLC) Block	Vadodara, Gujarat
	6	EB01	CSEB	Auroville, Tamil Nadu
	7	EC01	Expanded Clay Aggregate (ECA) Block	Rajkot, Gujarat
	8	CD01	Construction & Demolition (C&D) Waste Brick	Ahmedabad, Gujarat
	9	SB01	Surkhi Brick (Brick-bat Waste Brick)	Ahmedabad, Gujarat

Table 9: Average value of measured properties of other non-fired walling material samples

	S/N	Sample	Bulk Density ρ (kg/m^3)	Thermal conductivity λ $(W/m.K)$	Specific heat C_p $(J/kg.K)$	Compressive strength (MPa)	Water absorption (%)
Phase I	1	AB01	608	0.17	875.5	2.7	72
	2	AB02	623	0.19	831.0	3.4	73
	3	EB01	1630	0.59	908.3	1.76	22
	4	EB02	1773	0.75	934.8	13.05	16
	5	CC01	2032	0.81	912.8	10.04	9
	6	CC02	1961	0.66	928.9	6.8	13
	7	CB01	2122	1.55	920.0	29.6	7
	8	CS01	2071	0.71	969.2	18.79	12
	9	CL01	693	0.19	932.2	1.12	78
Phase II	10	CC01	2015	NA	886.71	6.6	9
	11	CC02	2117	NA	907.31	10.20	9
	12	CC03	2092	0.70	867.65	11.59	11
	13	CL01	760	0.20	1047.7	2.63	37
	14	CL02	744	0.21	891.68	2.86	44
	15	EB01	1993	0.97	1040.08	2.91	12
	16	EC01	613	0.19	1031.62	2.77	30
	17	CD01	1537	0.54	956.13	6.63	23
	18	SB01	1423	0.46	524.9	5.96	28

Figure 3 shows the variation of thermal conductivity with bulk density for non-fired bricks. Using Microsoft Excel, an exponential correlation is fit to the data[1]. Goodness of fit ($R^2 = 0.68$) indicates that bulk density has a significant impact on thermal conductivity.

For a given value of bulk density ρ ($\mathrm{kg/m^3}$), the following equation can be used to build an estimate of thermal conductivity λ ($\mathrm{W/m.K}$) for non-fired bricks:

$$\lambda = 0.1009e^{(0.0011\rho)} \qquad (600 < \rho < 2100) \qquad \text{... (3.2)}$$

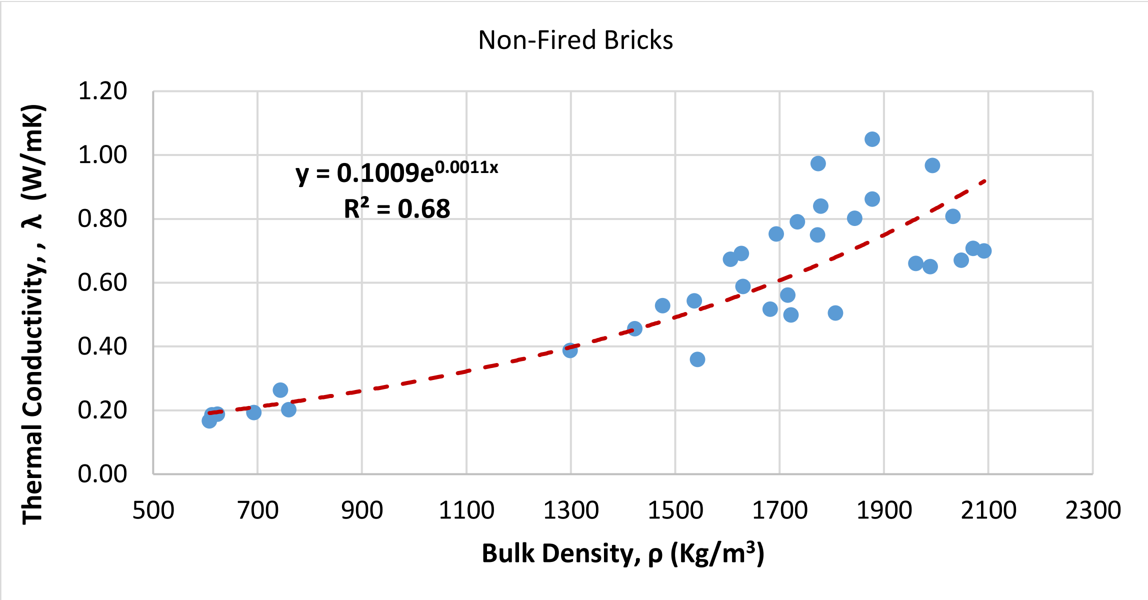


Figure 3: Thermal conductivity as a function of bulk density for non-fired bricks

3.3 Comparison of Material Properties

3.3.1 Thermal Conductivity

A comparison of thermal conductivity values (mean and range) of the commonly used walling materials is shown in Figure 4. The lowest thermal conductivity is for light weight concrete blocks (AAC and CLC), while the highest thermal conductivity is for solid concrete blocks. The mean thermal conductivity value of the hand-moulded fired clay bricks is 18% lower compared to that of fly ash bricks.

[1] For the analysis outlier data of samples CB01 (Phase I) and CC01 and CC02 (both Phase II) have been excluded.

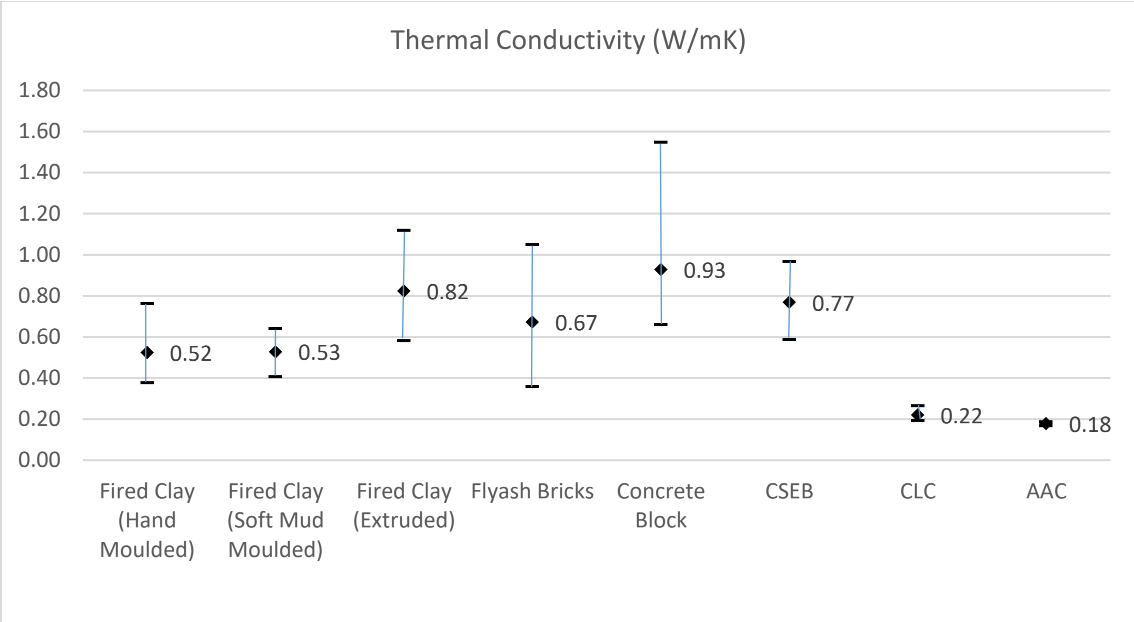


Figure 4: Comparison of thermal conductivity of various walling materials

A comparison of measured values of thermal conductivity of the commonly used solid bricks with the values given in Eco-Niwas Samhita[2] is given in Table 10.

Table 10: Comparison of thermal conductivity given in ENS and measured values in this study

Brick Type	Thermal Conductivity values as per Eco-Niwas Samhita (W/mK)	Measured Thermal Conductivity Values (W/mK)
Solid Fired Clay brick	Range: 0.62 – 0.98 Mean: 0.8	Range: 0.38 -1.12 Mean: 0.58
Solid Flyash brick	Only one value 0.856	Range: 0.36 -1.05 Mean: 0.67
Solid Cement Concrete blocks	Range: 1.396 -1.411 Mean:1.4	Range: 0.66-1.55 Mean: 0.93
CSEB	Range: 1.026 -1.303 Mean:1.18	Range: 0.59-0.97 Mean: 0.77
AAC	0.184	0.18
C&D waste brick	NA	0.54 (one sample)
Surkhi brick	NA	0.46 (one sample)
Expanded Clay Aggregate Brick	NA	0.19 (One sample)

[2] Refer Table 7: Thermal properties of building and insulation materials, page 23 Eco-Niwas Samhita 2018: Part I: Building Envelope

Following observations can be made:

a) The mean values of thermal conductivity in ENS for all common walling materials (except AAC block) are significantly higher (28-53%) compared to the mean values reported in this study. This means that using the thermal conductivity values given in ENS is likely to result in higher RETV estimations.

b) For a specific type of brick there is a large variation in thermal conductivity. For example, the measured thermal conductivity values for solid fired clay brick varies from 0.38 to 1.12 W/m.K. The values given in Eco-Niwas Samhita does not capture this large diversity and variation. Thus, it is recommended that the correlations (between dry density and thermal conductivity) developed in the study are included in the ENS.

The study provides thermal conductivity values for three new types of bricks – construction and demolition waste brick, surkhi brick and expanded clay aggregate bricks. Among these expanded clay aggregate brick shows a low thermal conductivity of 0.19 W/m.K, comparable to that of AAC blocks.

3.3.2 Bulk Density

A comparison of the bulk densities of various walling materials is shown in Figure 5. The bulk densities of the three most commonly used solid bricks/blocks – fired clay, fly ash and solid concrete, show significant variation, due to variations in the raw material properties (composition, particle size, etc) and the manufacturing process employed (e.g. the amount of pressure employed while shaping). AAC, CLC and expanded clay aggregate brick samples tested have low bulk densities (608-760 kg/m^3) on the other hand, extruded clay fired bricks and concrete blocks exhibit highest bulk densities (1900 -2150 kg/m^3).

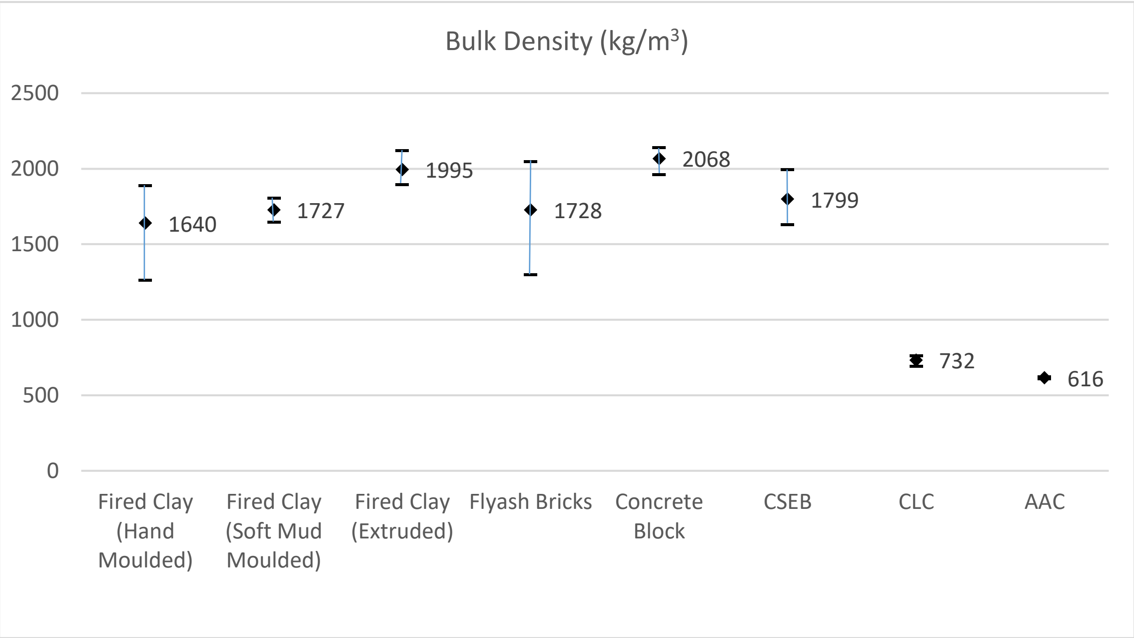


Figure 5: Comparison of bulk density of various walling materials:

3.3.3 Water Absorption

A comparison of the water absorption of various walling materials is shown in Figure 6. A large variation in the water absorption was observed for fired clay bricks and fly ash bricks and several samples exceeded the higher limit of 20% as prescribed in the BIS standards for these materials. Given the porous nature, CLC and AAC block exhibit very high-water absorption (37-78%).

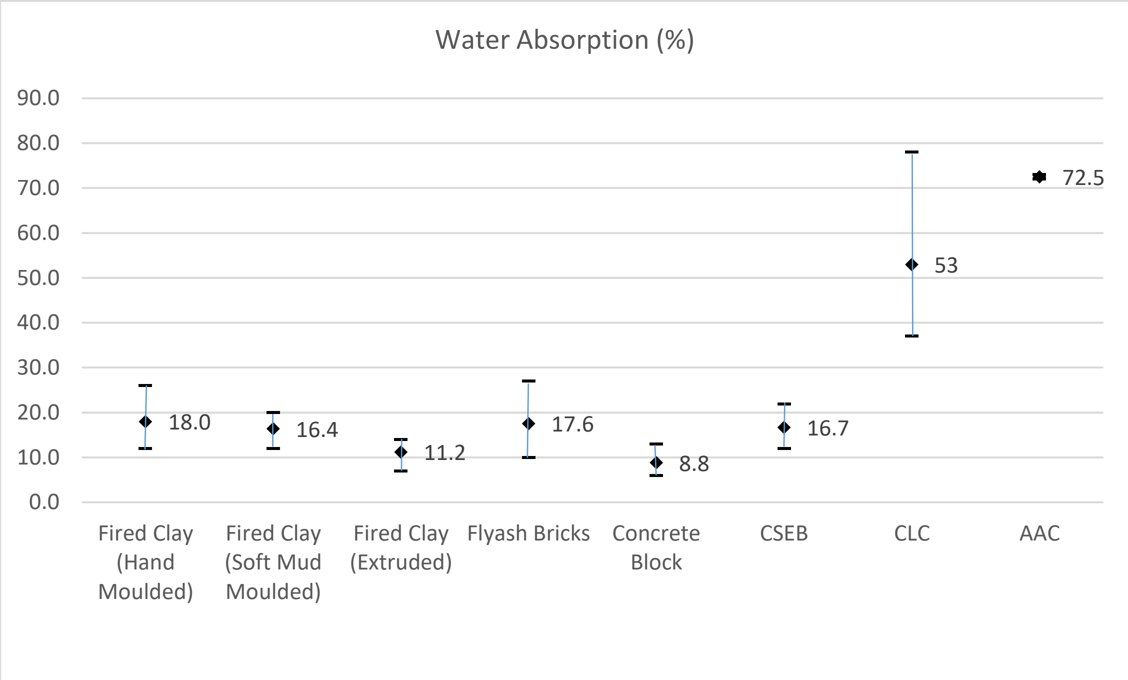


Figure 6: Comparison of water absorption of various walling materials

3.3.4 Compressive Strength

A comparison of the compressive strength of various walling materials is shown in Figure 7. Fired clay extruded bricks exhibits the highest compressive strength, while the AAC and CLC blocks exhibit the lowest compressive strength (1.12 -3.4 N/mm^2), extruded clay fired brick exhibits highest compressive strength (10.70- 58.2 N/mm^2).

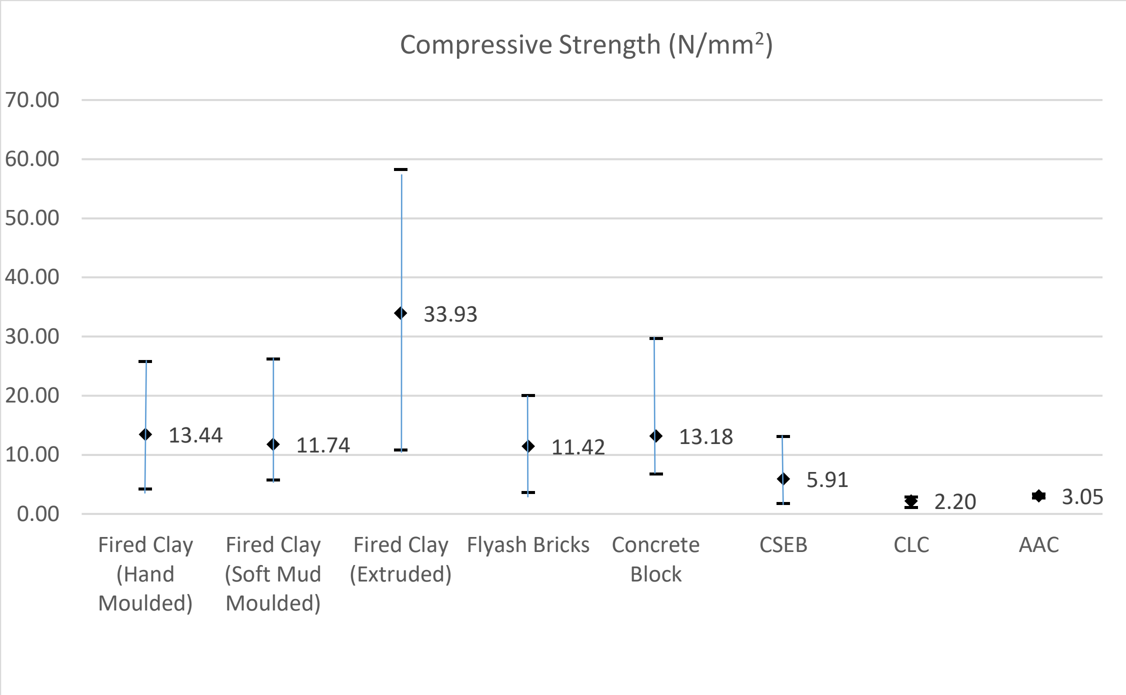


Figure 7: Comparison of compressive strength of various walling materials

3.3.5 Specific Heat Capacity

A comparison of the compressive strength of various walling materials is shown in Figure 8. The mean specific heat capacity of all the materials were found to vary between a narrow range of 853 -961 J/kg.K.

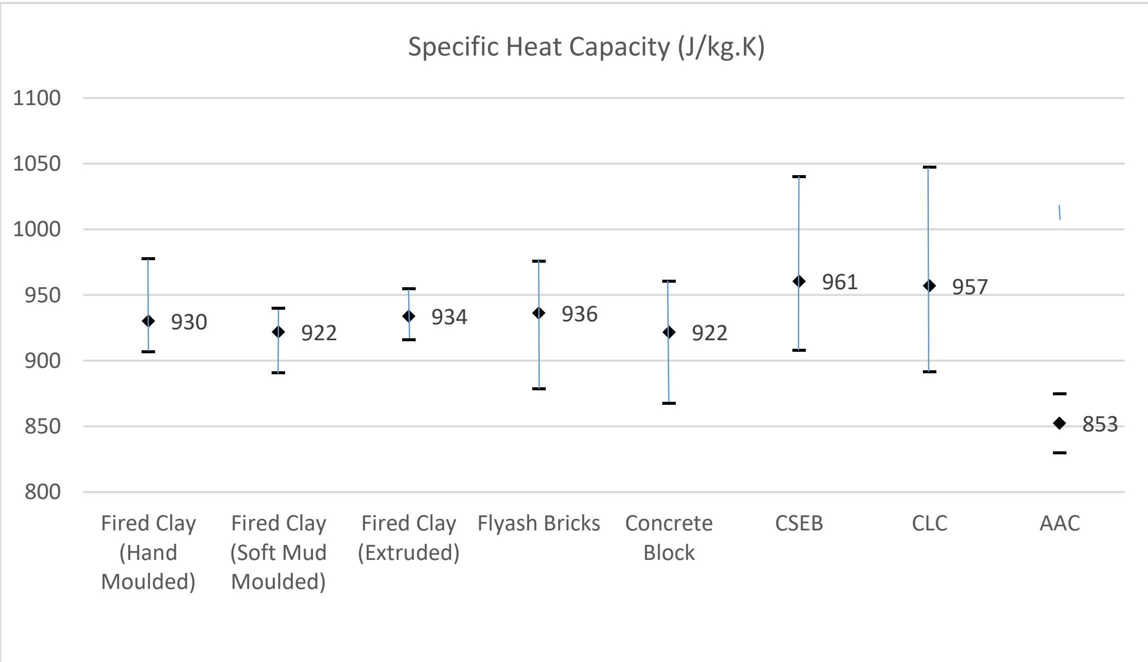


Figure 8: Comparison of specific heat capacity of various walling materials

3.4 Classification of Walling Materials

The tested solid bricks and blocks are classified into three categories (heavy density, medium density, and low density) and their thermo-physical characteristics are shown in Table 12. For easy interpretation, each cell is colour coded. The colour represents whether that parameter falls under Low, Medium, and High category as per classification given in Table 11.

Table 11: Classification of measured parameters based on mean values

	Low	Medium	High
Bulk Density (kg/m^3)	≤ 1000	$1000 < x \leq 1800$	$1800 < x \leq 2200$
Water absorption (%)	≤ 12	$12 < x \leq 30$	> 30
Compressive strength (N/mm^2)	≤ 3.5	$3.5 < x \leq 15$	> 15
Thermal Conductivity (W/m.K)	≤ 0.3	$0.3 < x \leq 0.8$	> 0.8
Volumetric Heat Capacity ($kJ/kg.m^3$)	$500 < x \leq 1000$	$1000 < x \leq 1750$	$1750 < x \leq 2250$

Table 12: Classification of solid bricks and blocks based on their density and their thermo-physical characteristics

Type of brick	Bulk Density (kg/m^3)	Water absorption (%)	Compressive strength (N/mm^2)	Thermal Conductivity (W/m.K)	Volumetric heat capacity (kJ/kg.m^3)	Remarks
Heavy Density						
Clay Fired (Extruded)	1995 (1895 -2119)	11.2 (7 -14)	33.93 (10.79 -58.2)	0.82 (0.58-1.12)	1863	• Physical: Low water absorption and high compressive strength. • Thermal: High thermal conductivity & high thermal mass. • Application: Suitable for use in load bearing construction. High dead load a disadvantage for mid- and high-rise buildings.
Concrete brick and block	2068 (1961-2141)	8.8 (6 -13)	13.18 (6.8 -29.6)	0.93 (0.66 -1.55	1906	
Calcium silicate brick	2071	12	18.79	0.71	2006	
Medium Density						
Clay Fired (Hand Moulded)	1640 (1264 -1887)	18 (12-26)	13.44 (4.16-25.8)	0.52 (0.38-0.76)	1525	• Physical: medium water absorption and medium compressive strength. • Thermal: Medium thermal conductivity as well as medium thermal mass. • Applications: These are the most used bricks and generally can be used both for load bearing as well as in frame construction.
Fly ash brick	1728 (1299 -1993)	17.6 10-27	11.42 (3.6 -20.0)	0.67 (0.36 -1.05)	1617	
Compressed Stabilized Earth Blocks	1799 1630 - 1993	16.7 12-22	5.91 1.76-13.50	0.77 0.59-0.97	1729	
C&D waste brick	1537	23	6.63	0.54	1469	
Surkhi brick	1423	28	5.96	0.46	NA	
Low Density						
AAC blocks	616 (608-623)	72.5 (72-73)	3.05 (2.7-3.4)	0.18 (0.17-0.19)	525	• Physical: High water absorption and low compressive strength. • Thermal: Low thermal conductivity as well as low thermal mass. • These bricks are not suitable for load bearing construction and generally used as walling material in framed construction. When used in mid- and high-rise construction, they bring additional advantage of low weight and hence savings in the structural cost.
CLC blocks	732 (693-760)	53 (37-78)	2.2 (1.12 -2.86)	0.22 (0.19-.0.26)	700	
Expanded Clay Aggregate Brick	613	30	2.77	0.19	632	

4. Calculation of RETV

The residential envelope transmittance value (RETV) is a measure of the average external heat gain into a building, normalized over all hours throughout the year and averaged over the entire envelope area of the building. It is quantified from three basic components of heat gain through external walls and windows of the building:

a) Heat conduction through opaque components (walls, opaque panels etc.)
b) Heat conduction through non-opaque components (transparent/translucent panels of windows, doors etc.)
c) Solar radiation through non-opaque components (transparent/translucent panels of windows, doors etc.)

The examination of RETV brings out the strong influence of external walls, glazing types and external shading devices on steady state thermal performance of the whole building envelope. As mentioned in Eco-Niwas Samhita (ENS) or Energy Conservation Building Code for residential buildings, for the purpose of energy conservation, the maximum permissible RETV has been set at $15\ \mathrm{W/m^2}$ (BEE, 2017).

In this chapter, for a sample building envelope, RETV has been calculated in correspondence to different external wall materials where other components affecting RETV are taken as constant. This enables the selection of building material in order to improve energy efficiency in residential buildings.

4.1 Sample Housing Project

A seven-storey housing project (SMARTGHAR-III) in Rajkot (Gujarat) has been selected to calculate RETV. The carpet area of each dwelling unit is $26.6\ \mathrm{m^2}$. There are three windows and one door exposed to the outside environment in each unit. The site plan and the typical floor plan for the project is provided in Figure 9. The windows are casement windows that are either fully (glass) or partially (PVC) glazed. There are eleven identical residential towers in the project out of which one tower has been selected for evaluating the impact of change in external wall material on the RETV.

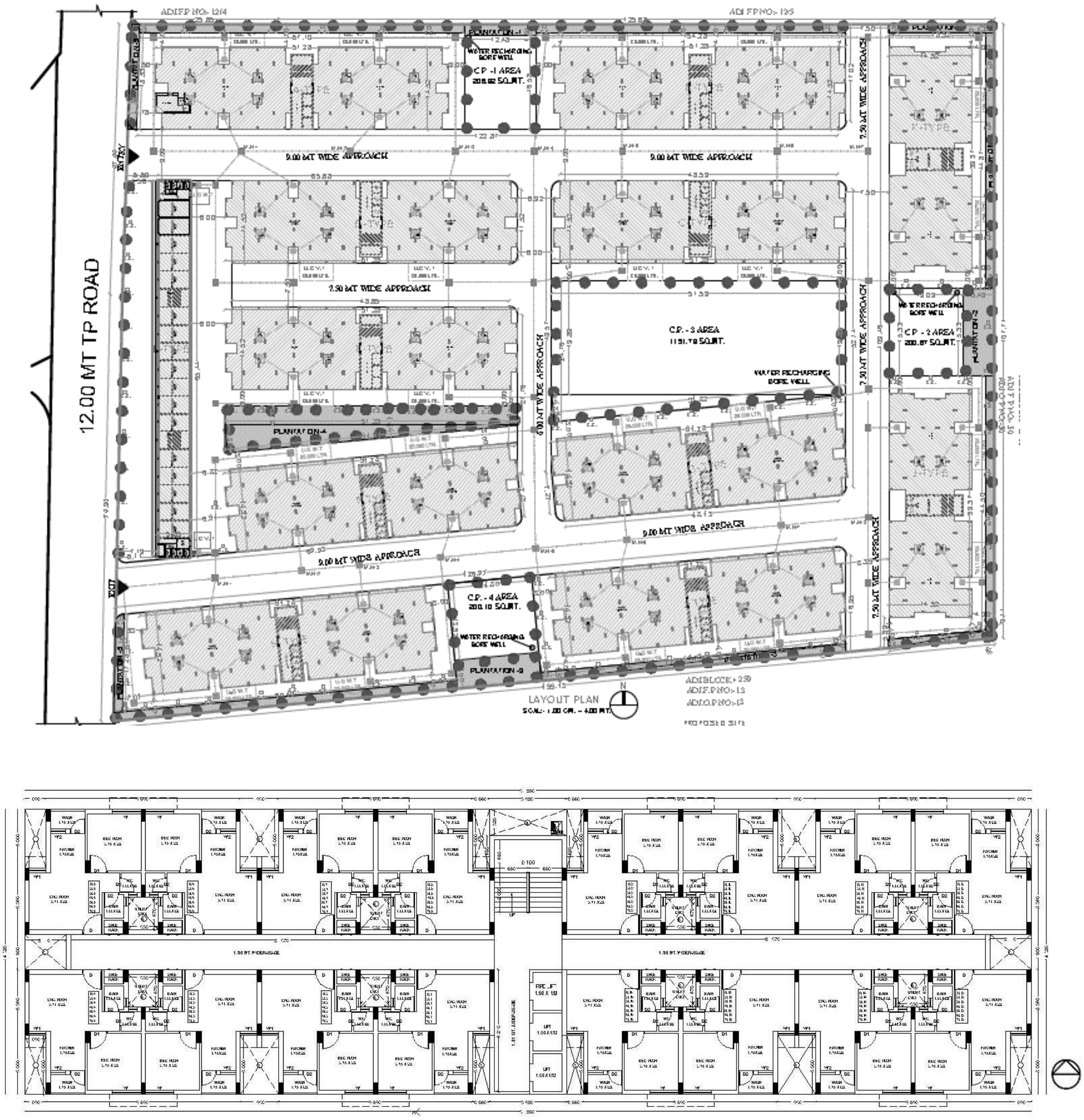


Figure 9: Site plan and typical unit plan of SMARTGHAR-III project, Rajkot

Table 13 provides *U*-value of 200mm thick wall of each tested walling unit, with 15mm plaster on both sides. Figure 11 shows the residential envelope transmittance values (RETV) for the given sample housing envelope taking different external wall materials.

Table 13: U-values for different walling material samples

Phase	S/N	Sample	Sample type	Thermal Transmittance Coefficient ($U-$value) ($W/m^2.K$) of 200 mm thick wall with 15 mm plaster on both sides
Phase I	1	RB01	Fired clay brick	1.60
	2	RB02	Fired clay brick	1.83
	3	RB03	Fired clay brick	2.39
	4	RB04	Fired clay brick	1.77
	5	RB05	Fired clay brick	2.56
	6	RB06	Fired clay brick	2.11
	7	RB07	Fired clay brick	1.70
	8	RB08	Fired clay brick	1.64
	9	RB09	Fired clay brick	1.37
	10	RB10	Fired clay brick	1.46
	11	RB11	Fired clay brick	1.63
	12	RB12	Fired clay brick	2.16
	13	RB13	Fired clay brick	1.81
	14	RB14	Fired clay brick	1.44
	15	RB15	Fired clay brick	1.34
	16	RB16	Fired clay brick	1.45
	17	RB17	Fired clay brick	1.42
	18	RB18	Fired clay brick	1.80
	19	RB19	Fired clay brick	1.92
	20	RB20	Fired clay brick	1.74
	21	RB21	Fired clay brick	1.72
	22	RB22	Fired clay brick	1.91
	23	RB23	Fired clay brick	2.07
	24	FB01	Fly ash brick	2.25
	25	FB02	Fly ash brick	2.16
	26	FB03	Fly ash brick	1.69
	27	FB04	Fly ash brick	1.37
	28	FB05	Fly ash brick	1.64
	29	FB06	Fly ash brick	1.30
	30	FB07	Fly ash brick	1.96
	31	FB08	Fly ash brick	1.67
	32	FB09	Fly ash brick	1.92
	33	FB10	Fly ash brick	1.63
	34	AB01	AAC block	0.70
	35	AB02	AAC block	0.70
	36	EB01	CSEB	1.81
	37	EB02	CSEB	2.08
	38	CC01	Concrete block	2.17
	39	CC02	Concrete block	1.94
	40	CB01	Concrete brick	2.93
	41	CS01	Calcium silicate blocks	2.02
	42	CL01	CLC block	0.80

Phase II	1	RB01	Fired-clay brick	1.78
	2	RB02	Fired-clay brick	1.8
	3	RB03	Fired-clay brick	1.43
	4	FB01	Fly-ash brick	2.49
	5	FB02	Fly-ash brick	2.22
	6	FB03	Fly-ash brick	1.76
	7	FB04	Fly-ash brick	1.96
	8	FB05	Fly-ash brick	1.99
	9	FB06	Fly-ash brick	2.39
	10	FB07	Fly-ash brick	2.15
	11	FB08	Fly-ash brick	2.09
	12	CC01	Concrete block	NA
	13	CC02	Concrete block	NA
	14	CC03	Concrete block	2.01
	15	CL01	Cellular light weight concrete block	0.83
	16	CL02	Cellular light weight concrete block	1.02
	17	EB01	Compressed stabilized earth block	2.39
	18	EC01	Expanded Clay Aggregate Block	0.79
	19	CD01	Construction & Demolition (C&D) Waste Brick	1.72
	20	SB01	Surkhi Brick (Brick-bat Waste Brick)	1.55

The U-value of the 230 mm thick wall made from different type of solid bricks was found to vary between 0.7 W/m^2.K to 2.93 W/m^2.K as shown in Figure 10.

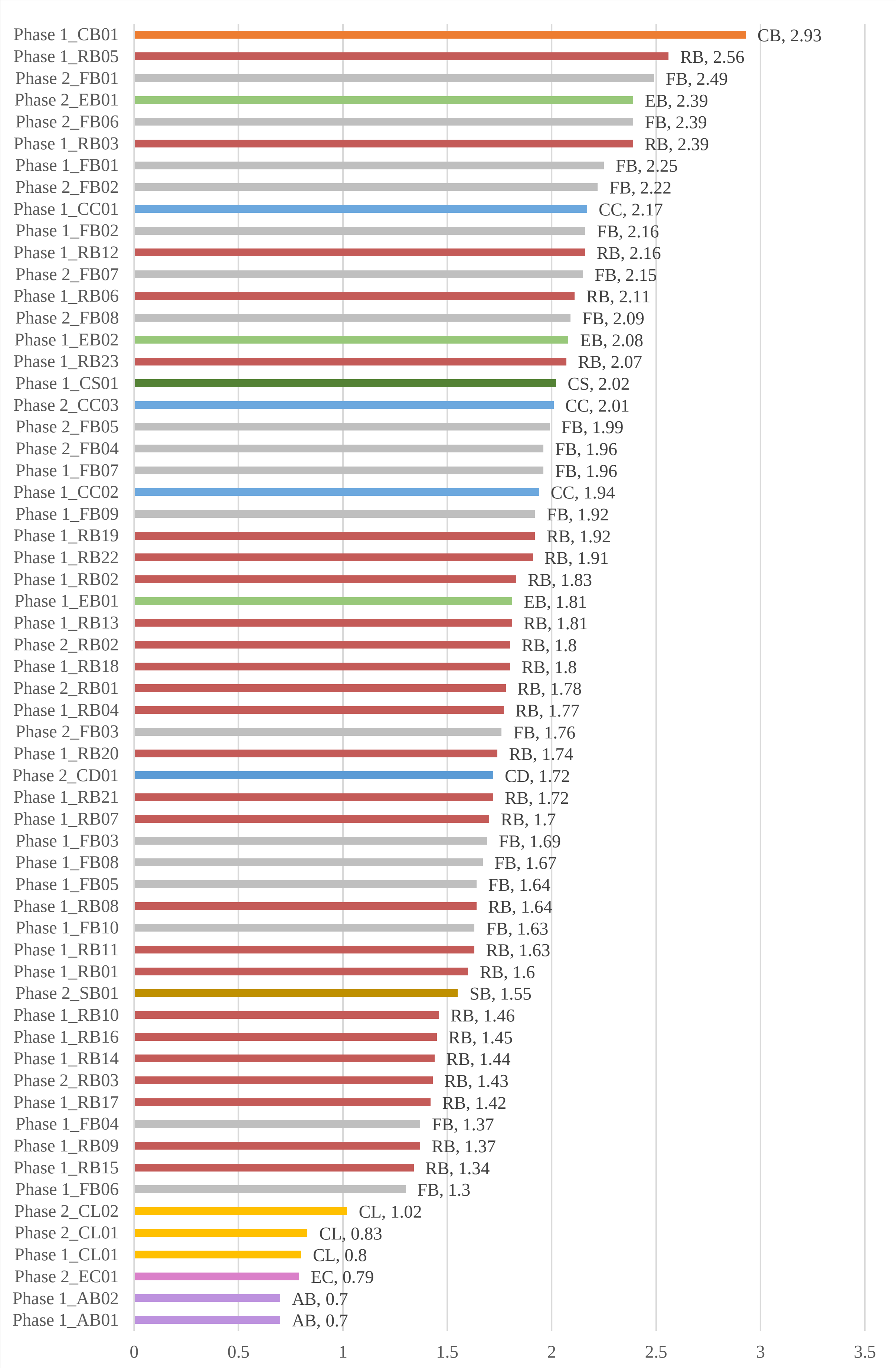


Figure 10: Thermal transmittance values corresponding to various walling materials for a sample envelope

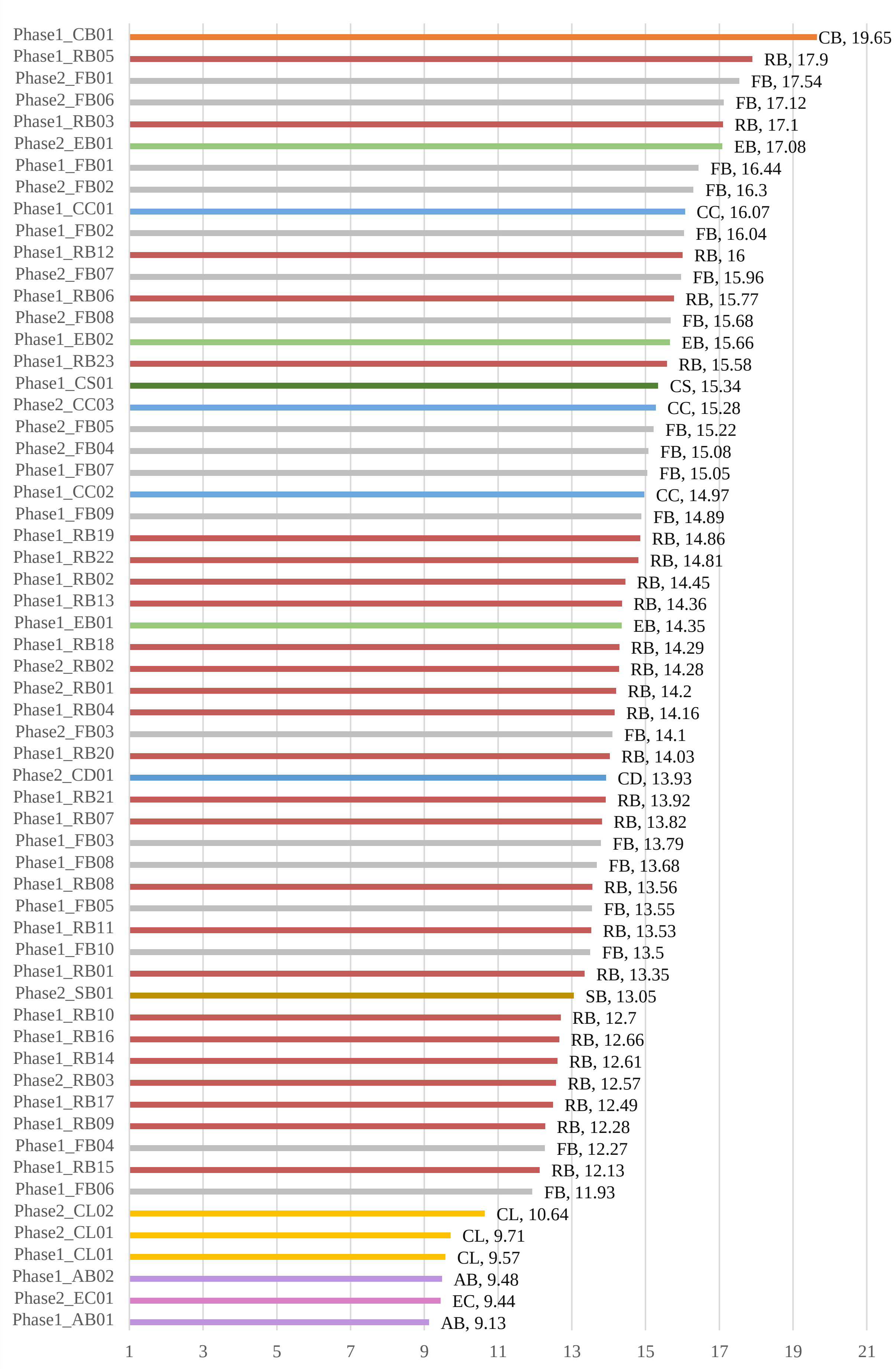


Figure 11: RETV values corresponding to various walling materials for a sample envelope

Following conclusions can be drawn based on the analysis of the U-value of the standard wall with 230 mm thickness (200 mm brick + 15 mm plaster) and RETV calculations for a specific tower of Smart GHAR 3 project located at Rajkot (composite climate):

- The choice of brick to construct external wall (U-value ranging between 0.7 W/m^2K to 2.93 W/m^2K) has a large impact on the RETV value. The maximum value of RETV for Smart GHAR-3 is 19.65 W/m^2, which is more than double the minimum RETV of 9.13 W/m^2. Thirty-one, out of forty-two solid brick types meet the RETV threshold of 15 W/m^2 as specified by Eco-Niwas Samhita, 2018.
- AAC and CLC blocks have the lowest U value (~ 0.8 W/m^2K) and lowest RETV value (~ 9.5 W/m^2), which is well below the RETV threshold of 15 W/m^2.
- Solid concrete and calcium silicate bricks exhibit high U value (~ 2.0 to 3.0 W/m^2K) and RETV, generally exceeding the threshold of 15 W/m^2.
- Commonly available hand moulded fired clay (excluding extruded bricks) and fly ash bricks exhibit moderate U value (1.3 – 2.25 W/m^2K) and in majority of cases meet the RETV threshold of 15 W/m^2.

5. Conclusions

1. The project collected and tested sixty-two samples of 11 types of solid bricks and blocks from 14 states of the country covering variation in material composition and manufacturing process employed. Each of the sixty-two sample sets were characterized for the following properties.
   - Thermal conductivity
   - Specific heat
   - Bulk density
   - Water absorption
   - Compressive strength.
2. The tested bricks can be classified under three categories

   Heavy density bricks (>1800 kg/m^3): Extruded fired clay brick, solid concrete and calcium silicate brick can be classified as heavy density bricks. Characteristics based on mean of the tested values are:

   - Physical characteristics: Low water absorption (≤12%) and high compressive strength (>15 N/mm^2).
   - Thermal characteristics: High thermal conductivity (> 0.8 W/m.K) and high volumetric heat capacity (> 1750 kJ/kg.m^3).

   Application: Suitable for use in load bearing construction. High dead load is a disadvantage for their application in mid- and high-rise buildings. The material can be used to provide high thermal mass.

   Medium density bricks (1000-1800 kg/m^3): Hand moulded clay fired bricks, fly ash bricks, CSEB blocks and C&D/Surkhi bricks can be classified as medium density bricks. Characteristics based on mean of the tested values are:

   - Physical characteristics: Medium water absorption (12-30%) and medium compressive strength (3.5 -15 N/mm^2)
   - Thermal characteristics: Medium thermal conductivity (0.3-0.8 W/m.K) as well as medium volumetric heat capacity (1000 -1750 kJ/kg.m^3)

   Application: These are the most commonly used bricks, and they can be used both for load bearing as well as in frame construction.

   Low density bricks (< 1000 kg/m^3): AAC, CLC and expanded clay aggregate bricks can be classified as low-density bricks. Characteristics based on mean of the tested values are:

   - Physical characteristics: High water absorption (>30%) and low compressive strength (<3.5 N/mm^2).

- Thermal characteristics: Low thermal conductivity (≤ 0.3 W/m.K) as well as low volumetric heat capacity (500 -1000 kJ/kg.m^3) .

Application: These bricks are not suitable for load bearing construction and generally used as walling material in framed construction. When used in mid- and high-rise construction, apart from better thermal insulation, they bring additional advantage of low weight and hence savings in the structural cost. Suitable care needs to be taken during construction to avoid formation of cracks and water leakage.

3. For a specific type of brick, a large variation in thermal conductivity and bulk density was observed. For example, the measured thermal conductivity values for solid fired clay brick were found to vary from 0.38 to 1.12 W/m.K. Correlations have been developed between the bulk density and the thermal conductivity for fired clay bricks and non-fired bricks, these are as follows:

- Fired clay brick: For a given value of bulk density ρ $(\mathrm{kg/m^3})$, the following equation can be used to make an estimation of thermal conductivity λ $(\mathrm{W/m.K})$.

$$\lambda = 0.0652e^{(0.0012\rho)} \qquad (1250 < \rho < 2150)$$

- Non-fired brick: For a given value of bulk density ρ $(\mathrm{kg/m^3})$, the following equation can be used to build an estimate of thermal conductivity λ $(\mathrm{W/m.K})$.

$$\lambda = 0.1009e^{(0.0011\rho)} \qquad (600 < \rho < 2100)$$

4. It is recommended that BEE can take action to amend the database of thermal properties values given in Table 7 of Eco-Niwas Samhita: Part I (2018). The results show that the mean values of thermal conductivity given in ENS for all common walling materials (except AAC block) are significantly higher (28-53%) compared to the mean values reported in this study. This means that using the thermal conductivity values given in ENS is likely to result in higher RETV estimations. Also, the correlations can be included in Eco-Niwas Samhita so that by measuring the bulk density, thermal conductivity of the brick can be determined for RETV calculations.
5. U-value of 200 mm bricks wall with 15 mm plaster on both sides (total wall assembly thickness of 230 mm) was calculated for the tested bricks. The highest U-value of 2.93 W/m^2.K was more than four times higher compared to the lowest U-value of 0.7 W/m^2.K. Further RETV value for a sample affordable housing project located at Rajkot was calculated for the tested bricks. It was observed that the choice of brick to construct external wall has a large impact on the RETV value. For the given project, the maximum value of RETV was 19.65 W/m^2, which is more than double the minimum RETV of 9.13 W/m^2. Thus, choice of brick for the external walls is a key to meet the RETV standard of Eco-Niwas Samhita.

6. Annexures

Annexure I: Definitions

Thermal conductivity

As per IS 3069:1994 thermal conductivity is defined as **"**the time rate of heat flow through unit thickness of an infinite slab of a homogeneous material in a direction perpendicular to the surface, induced by unit temperature difference". It is expressed in W/m-K as per the measurement standard ISO/DIS 22007-2:2015.

Volumetric Specific heat or Heat capacity per unit volume

As per IS 3069:1994 (BIS, 1994) volumetric specific heat or heat capacity per unit volume is defined as "the quantity of heat required to raise the temperature of unit volume by one degree". It is expressed in MJ/m^3K as per measurement standard ISO/DIS 22007-2:2015.

Water absorption

As per IS2248:1992 (BIS, 1992a) water absorption is defined as "the increase in weight of a test specimen after immersion in water, at a constant temperature and for a specified period, expressed as a percentage of the dry weight".

Bulk density

As per ASTM C20 "the bulk density of a specimen in grams per cubic centimetre is the quotient of its dry weight divided by the exterior volume, including pores". It is expressed in Kg/m^3 as per IS 3069:1994. For walling units such as bricks and blocks, the dry density is equivalent to bulk density.

Compressive strength:

As per IS 3069:1994 the compressive strength of a material is defined as "the capacity of a material to withstand mechanical pressure up to the point of fracture, and in the case of materials which do not fail by shattering, the compressive strength may be deduced arbitrarily from a load deformation curve." Measured in N/mm^2 as per measurement standard IS 3495 (part1):1992.

Annexure II: Methodology for measurement of thermal properties

This Annexure covers an overview of the methodology followed for testing of thermal properties listed in Section 2.2. The overview includes the number of samples required for each test, tagging the received samples, and testing procedure.

Number of Samples Required for Each Test

Based on the applicable standards, a definite number of samples were required for testing each parameter mentioned in Section 2.2. Table 14 shows the number of samples needed for each test as per standards (cut or full-sized samples). In case of bricks full size samples were required and the blocks were cut to smaller sizes to match the brick size for all tests.

Table 14: Number of cut or full-sized samples needed for each test as per standards

S/N	Material Type	Number of samples needed for each test as per standard			
		Thermal Conductivity, Specific heat	Dry Density	Water Absorption	Compressive strength
1	Fired clay bricks (RB)	3	5	5	5
2	Fly ash Bricks (FB)	3	5	5	5
3	Solid concrete brick (CB)	3	5	5	5
4	Solid concrete blocks (CC)	3	3	3	12
5	Calcium silicate block (CS)	3	5	5	5
6	AAC blocks (AB)	3	3	3	12
7	Cellular light weight concrete block (CL)	3	3	3	12
8	CSEB (EB)	3	5	5	5
9	Demolition waste brick	3	5	5	5
10	Expansion Clay Aggregate	3	5*	5	5
11	Surkhi brick	3	5	5	5

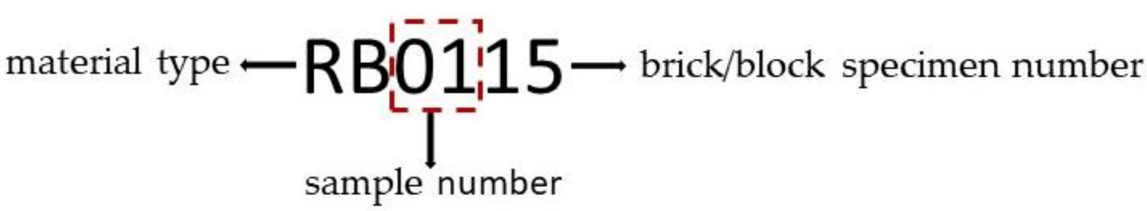


Figure 12: Illustration to explain sample tag

Figure 13: photograph of tagged bricks belonging to set 01 (left) & set 05 (right)

Sample tag

Each of the received sixty-two material samples were visually inspected for damages and were marked with a sample tag name based on the material type (abbreviated name of the material), the sample and specimen number as seen in Figure 12. Table 15 shows the different abbreviations assigned to the tested materials. For example, first sample set of fired clay bricks despatched to CARBSE was tagged as 'RB01**'** where, RB represents fired clay brick and '01' is the 1st sample. Further, for testing purpose individual brick/test specimens were named in a numerical order. For example, each brick within the first sample set of fired clay brick was tagged from RB0101 to RB0120 (i.e., 20 bricks of set 01 of fired clay brick) as seen in Figure 13. The tagged samples were safely stored in their respective packaging until the time of testing. The tested samples were marked with the letter 'T' and stored separately in case further retesting was necessary.

Table 15: Different types of material samples received for testing and the corresponding abbreviations assigned to them.

S. N	Abbreviation	Material type
1	RB	Fired clay brick
2	FB	Fly ash brick
3	CB	Solid concrete brick
4	CC	Solid concrete block
5	CS	Calcium silicate block
6	AB	Autoclaved aerated concrete block (AAC)
7	CL	Cellular light weight concrete block (CLC)
8	EB	Compressed stabilized earth block (CSEB)
9	CD	Demolition waste brick
10	EC	Expansion Clay Aggregate
11	SB	Surkhi brick

Testing procedure

Thermal Conductivity:

Thermal conductivity was determined for each material type using the transient plane heat source (hot disc) method and the reference standard used is ISO/DIS 22007-2:2015. The main instrument used is Hot Disk TPS 2500S as seen in Table 3. Additionally, the Inert Gas Oven was used for preconditioning the samples as described below.

Figure 14: Photograph of thermal constant analyser testing brick samples using transient plane source method

Preconditioning

1. Three masonry unit samples as shown in Figure 15 was dried in the inert gas oven at a temperature of 105 °C for the period of 24 hrs. as seen in Figure 16.
2. After drying, all 3 specimens were conditioned at 22 °C and 50 % RH until less than 1 % mass change is observed over 24 hrs. period (maintained in the lab) (ISO, 2015).

Measurement

Thermal conductivity was measured at 25 ± 1 °C and 50% ± 10% RH conditions using Thermal constant analyzer in accordance with transient plane source method as seen in Figure 14Figure 14. The procedure was followed through as per ISO/DIS 22007-2:2015.

Calculation

As per standard procedure the hot disk probe operating as a temperature sensor was placed sandwiched between two brick/block specimens for measurement. 10 measurements were carried out by using random combinations of 3 specimens as shown in Figure 17 and the average was reported.

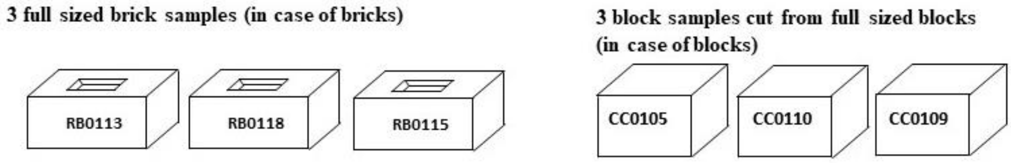


Figure 15: Illustration showing number of masonry units needed for testing thermal conductivity and specific heat capacity

Figure 16: Photograph of the Inert Gas Oven (left) & bricks prepared for drying (right)

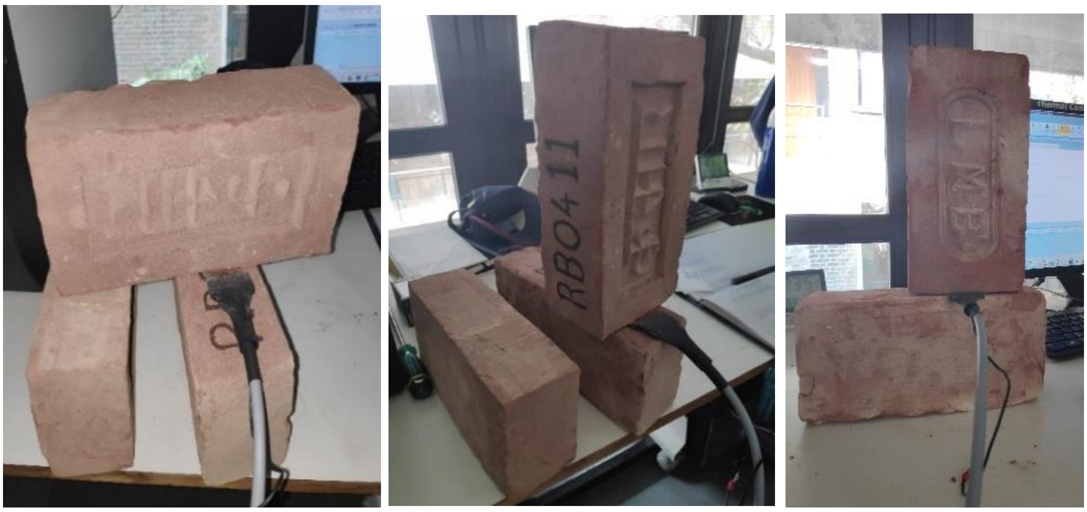


Figure 17: Photographs demonstrating different combinations of brick specimens placed for measurement and hot disk probe sandwiched between two samples of fired clay brick

Specific Heat:

While preparing the brick samples for hygrothermal measurements, significant random cavity spots were observed in the brick samples. Hence, specific heat capacity of brick was measured using gold disk sensor in the Transient Plane Source set up. The refined measurement procedure is described below:

Procedure

1. Initially a reference measurement was carried out by keeping the gold disk sensor empty as seen in Figure 18.

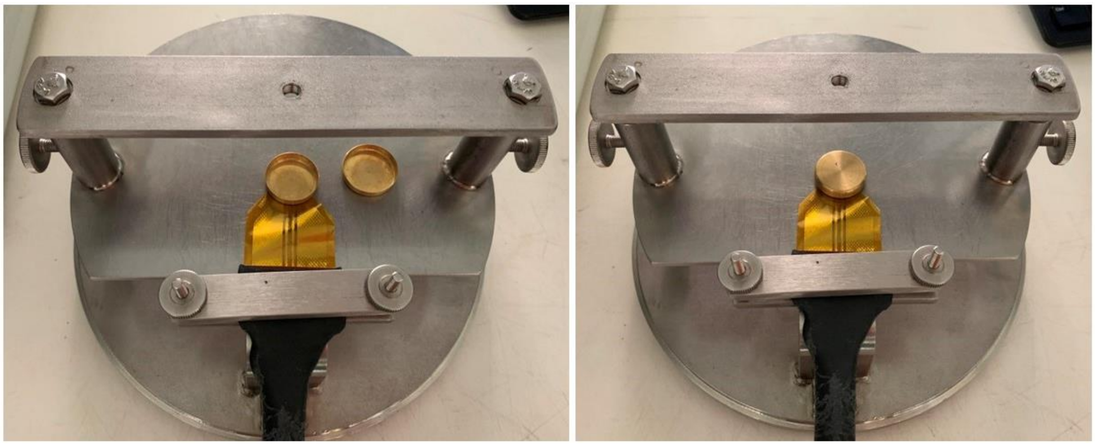


Figure 18: Reference Measurement

2. A small homogeneous piece of brick (test sample) without any air cavity was cut from the conditioned brick as seen in Figure 19.

Figure 19: Test Sample Preparation

3. As seen in Figure 20, a beaker was fully filled with water letting the excess water drop out of it. The test sample was dropped into the beaker and the weight of the displaced water due to its submersion was measured. Using the values of the weight of the displaced water and the density of water, the exterior volume of the test sample was calculated.

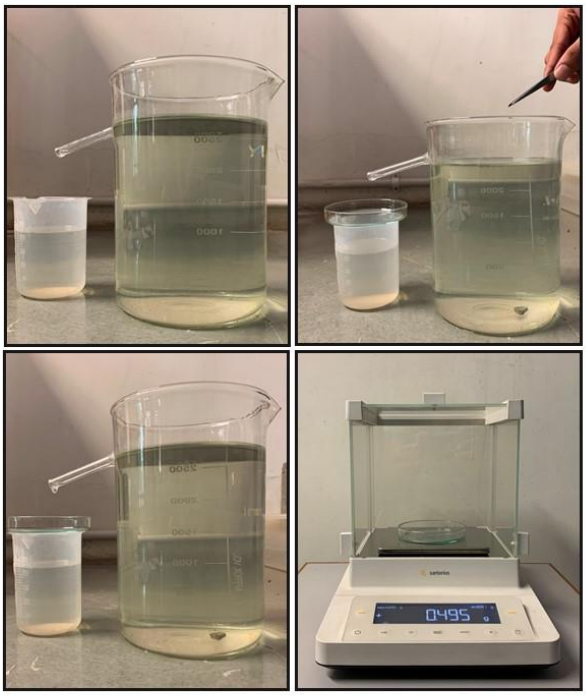


Figure 20: Exterior Volume Measurement

4. The test sample was dried, and the weight of the dried test sample was measured as seen in Figure 216.

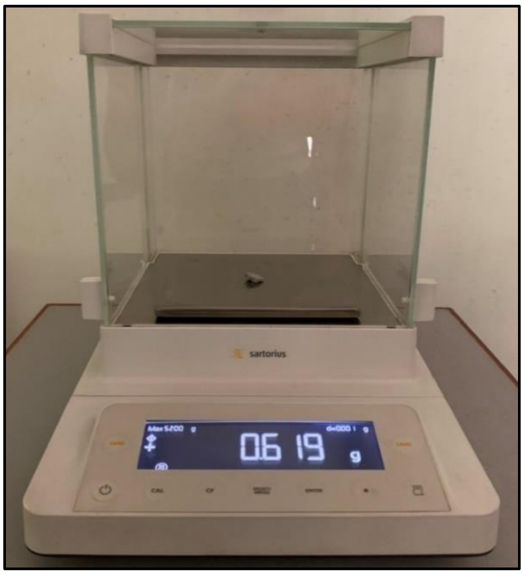


Figure 21: Weight measurement of the dried test sample

5. Five measurements of specific heat capacity (per unit mass) were carried out by keeping the sample in the gold disk sensor as seen in Figure 227, and providing values of the reference measurement, the exterior volume and the weight of the test sample of the brick.

Figure 22: Specific heat capacity measurement using gold disk sensor

Dry density:

Dry/ Bulk density was measured based on ASTM C20. The Instruments used were Inert gas oven, water bath and precision weighing. Since measurement for dry density and water absorption (explained further in the next section) involves the same procedure as per respective standards, the same set of samples were used to characterize both parameters.

Measurement

1. Five bricks or three block sample as seen in Figure 238, were dried at a temperature of 105 °C until a constant mass was achieved.
2. After drying, the sample was cooled to room temperature and its weight was obtained, denoted by dry mass (D) as seen in Figure 24.
3. After dry mass measurement, the sample was submerged into boiling water for the period of 2 hours as seen in Figure 25.

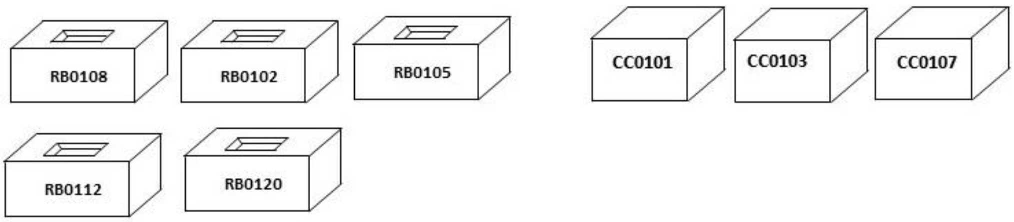


Figure 23: Illustration showing number of masonry units allotted for testing dry density and water absorption

Figure 24: Photograph showing dried sample being weighed to get dry mass (D)

Figure 25: Photograph showing dried brick samples being boiled (left) and brick samples immersed in water afterwards (right) as per the procedure

4. After the boiling period, samples were cooled to room temperature while still completely covered with water. Samples were kept immersed in water for 22 hrs. as seen in Figure 25 before weighing again.
5. Suspended weight (S) of each sample was measured while suspended in water as per the procedure in ASTM C20 seen in Figure 26.

6. After determining the suspended weight, excess water was removed by blotting each sample lightly with a moistened smooth linen or cotton cloth.
7. Saturated weight (W) was obtained by weighing the sample in air as per the procedure in ASTM C20 seen in Figure 26.

Calculation

After measuring Dry Weight (D), Suspended Weight (S), and Saturated Weight (W) in Kg below calculations were carried out to determine the Block Density (ASTM International, 2010).

Exterior Volume, V (m^3) = W- S

Dry/bulk Density = D/V (Kg/m^3)

Figure 26: Photograph showing measurement of suspended weight (S)(left) and saturated weight (W)(right) as per the procedure

Water Absorption:

Water absorption was measured based on IS 3495 (for bricks) and IS 2185 (for blocks). The Instruments used were Inert gas oven and precision weighing scale as shown in Figure 161 and Figure 24,Figure 250 (right) and Figure 261 (right).

Measurement

1. Five brick or three block samples, as seen in Figure 23 were dried at a temperature of 105 °C until a constant mass was achieved.
2. After drying, the sample was cooled to room temperature and its weight was obtained, denoted by dry weight (M1) as seen in Figure 24.
3. After dry weight measurement, the sample was submerged into clean water kept at a temperature of 27 ± 2°C for 24 hours as seen in Figure 250 (right).
4. After 24 hours, excess water was removed by blotting each sample lightly with a moistened smooth linen or cotton cloth and Saturated weight (M2) was obtained by weighing the sample.

Calculation

After measuring Dry Weight (M1), and Saturated Weight (M2) in Kg below calculations were carried out to determine the Water Absorption (Bureau of Indian Standards (BIS), 1992).

$$\text{Water Absorption} = \frac{M2-M1}{\text{M1}} \text{ X } 100\ \%$$

Compressive Strength

Compressive strength was measured based on IS 3495 for bricks and IS 2185 for blocks. The instrument used was the Compression testing machine.

Preconditioning

1. Five brick/twelve block samples as seen in Figure 27 with smooth even surfaces were immersed in water at room temperature for 24 hrs.
2. The samples were removed, and surplus moisture was drained out.

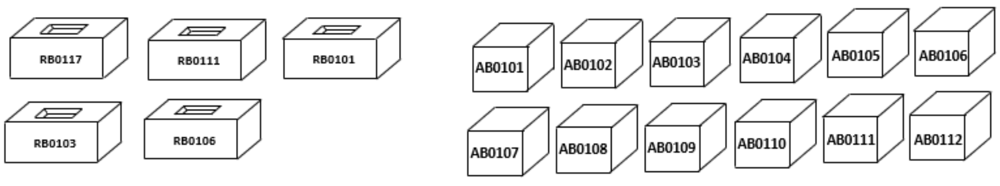


Figure 27: Illustration showing the number of samples required for the compressive strength test. Left- 5 full sized samples, in case of bricks; Right- 12 samples cut from full blocks, in case of blocks

3. The frog in case of bricks and any other voids in the brick bed face was made even with cement mortar filling as seen in Figure 28.
4. The samples were then stored under damp jute bags for 24 hrs. followed by immersion in clean water for 3 days.
5. After this process, excess moisture was wiped clean from the samples.

Measurement

1. The clean sample was placed within the machine with mortar fill facing upwards between two to three plywood sheets of 3mm thickness, centred between the two plates of the machine as seen in Figure 29, and load was applied axially at a uniform rate of 14 N/mm2 per minute till failure occurred.
2. Maximum load at failure was noted.

Calculation

Compressive strength was calculated as:

$$\text{Compressive strength in } N/mm^2 = \frac{\text{Maximum load at failure in N}}{\text{Average area of the bed faces in } mm^2}$$

Figure 28: Photograph of mortar filled bricks ready to be tested

Figure 29: Photograph of Compression testing machine

Annexure III: Measurement Datasheets

Datasheet 01

General information	
Sample type	Hand moulded burnt-clay brick 
Sample number	RB01
Date of collection	January 9, 2019
Location	Panchpara Gram Panchayat (Near Hooghly River) Satyen Bose Road, Kolkata, West Bengal
Raw material	River silt
Production processes	• **Clay preparation**: Mechanical (using earth excavator and pug mill) • **Shaping**: Hand moulding • **Drying**: Natural drying • **Firing**: Bricks are fired in an induced draught Zigzag kiln • **Fuel**: Coal (Jharia coalfield, Jharkhand)
Fuel consumption	13.5 ton per lakh bricks
Production capacity	22000 – 24000 bricks per day
Address/Contact	LMB Bricks, Mr. Ashok Tiwari, President, Bengal Brick Field Owners Association

Thermal and physical properties	
Dry density, ρ (kg/m^3)	1599
Thermal conductivity, λ (W/m-K)	0.4847
Specific heat, C (KJ/kg-K)	0.9078
Water absorption, (%)	21
Compressive strength, σ (N/mm^2)	14.83

Datasheet 02

General information	
Sample type	Fly ash brick 
Sample number	FB01
Date of collection	January 9, 2019
Location	Barasat, Kolkata, West Bengal
Raw material	Fly ash, cement, red sand, stone dust
Production processes	• **Mixture preparation**: Pan mixer is used to mix raw material (90kg fly ash +165kg red sand + 80kg stone dust+ 25 kg cement) • **Shaping**: Bricks are shaped by a vibro-hydraulic power compacting machine and then cured by water.
Electricity consumption	15,500 kWh per month
Production capacity	10,000 bricks in 8 hours.
Address/Contact	Maya Ashtech Mr. Devanand Jewani (+91-9830804971)

Thermal and physical properties	
Dry density, ρ (kg/m^3)	1878
Thermal conductivity, λ (W/m-K)	0.8619
Specific heat, C (KJ/kg-K)	0.9382
Water absorption, (%)	12
Compressive strength, σ (N/mm^2)	19.98

Datasheet 03

General information	
Sample type	Hand moulded burnt clay brick 
Sample number	RB02
Date of collection	January 31, 2019
Location	Jhajjar, Haryana
Raw material	Excavated clay
Production processes	• **Clay preparation**: Mechanical (using earth excavator and pug mill) • **Shaping**: Hand moulding • **Drying**: Natural drying • **Firing**: Bricks are fired in an induced draught Zigzag kiln • **Fuel**: Coal (USA), Sawdust
Fuel consumption	8-ton coal per lakh bricks
Production capacity	36000 bricks per day
Address/Contact	Jindal Mechno Bricks Mr. Satpal Jindal (9811273798)

Thermal and physical properties	
Dry density, ρ (kg/m^3)	1777
Thermal conductivity, λ (W/m-K)	0.5988
Specific heat, C (KJ/kg-K)	0.9216
Water absorption, (%)	15
Compressive strength, σ (N/mm^2)	16.54

Datasheet 04

General information	
Sample type	Hand moulded burnt clay brick 
Sample number	RB03
Date of collection	January 31, 2019
Location	Jhajjar, Haryana
Raw material	Excavated clay
Production processes	• **Clay preparation**: Mechanical (using earth excavator and pug mill) • **Shaping**: Bricks are made by two extrusion machines of 50 and 150 ton per day capacity. • **Drying**: Bricks are dried in tunnel dryer • **Firing**: Bricks are fired in two tunnel kilns of 50 and 150 ton per day capacity.
Address/Contact	Jindal Mechno Bricks Mr. Satpal Jindal (9811273798)

Thermal and physical properties	
Dry density, ρ (kg/m^3)	2119
Thermal conductivity, λ (W/m-K)	0.9694
Specific heat, C (KJ/kg-K)	0.9161
Water absorption, (%)	7
Compressive strength, σ (N/mm^2)	58.21

Datasheet 05

General information	
Sample type	Fly ash brick 
Sample number	FB02
Date of collection	January 31, 2019
Location	Jhajjar, Haryana
Raw material	Fly ash
Production processes	• Fully mechanized unit
Address/Contact	Jindal Mechno Bricks Mr. Satpal Jindal (9811273798)

Thermal and physical properties	
Dry density, ρ (kg/m^3)	1844
Thermal conductivity, λ (W/m-K)	0.802
Specific heat, C (KJ/kg-K)	0.9248
Water absorption, (%)	16
Compressive strength, σ (N/mm^2)	12.43

Datasheet 06

General information	
Sample type	Hand-moulded burnt-clay brick 
Sample number	RB04
Date of collection	February 5, 2019
Location	Damrahi Ghat, Patna, Bihar
Raw material	Excavated clay
Production processes	• **Clay preparation**: Mechanical (using earth excavator and pug mill) • **Shaping**: Hand moulding • **Drying**: Natural drying • **Firing**: Bricks are fired in a natural draught Zigzag kiln • **Fuel**: Coal (Amlo/Kalyani coalfield, Jharkhand)
Fuel consumption	17 ton per lakh bricks
Production capacity	25,000 bricks per day
Address/Contact	Kumar bricks Mr. Vijay

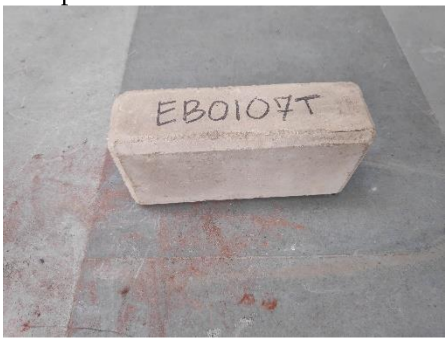
Thermal and physical properties	
Dry density, ρ (kg/m³)	1654
Thermal conductivity, λ (W/m-K)	0.5668
Specific heat, C (KJ/kg-K)	0.9175
Water absorption, (%)	19
Compressive strength, σ (N/mm²)	23.08

Datasheet 07

General information	
Sample type	Fly ash brick 
Sample number	FB03
Date of collection	February 5, 2019
Location	Sampatchak Nahar, Patna, Bihar
Raw material	Fly ash, cement
Production processes	• **Mixture preparation**: Pan-mixer is used to mix raw material • **Shaping**: Bricks are shaped by a vibro-hydraulic power compacting machine and then cured by water.
Production capacity	• 3 lakh bricks yearly • 4000 bricks per day (based on demand) • Installed capacity is 12,000 brick per day.
Address/Contact	Magadh Bricks Ravi Ranjan Prakash (9955949074)

Thermal and physical properties	
Dry density, ρ (kg/m^3)	1475
Thermal conductivity, λ (W/m-K)	0.5278
Specific heat, C (KJ/kg-K)	0.962
Water absorption, (%)	23
Compressive strength, σ (N/mm^2)	9.02

Datasheet 08

General information	
Sample type	Compressed stabilized earth block 
Sample number	EB01
Date of collection	February 5, 2019
Location	Jaunapur, Delhi
Raw material	Soil, Sand, and Cement
Production processes	• **Mixture preparation**: Soil sand and cement, in the ratio of 8:2:1 by volume, are mixed with pan-mixer (make: TARA). • **Shaping:** Bricks are pressed into shape by a semi-mechanized press (make: TARA) and manual press (make: BALRAM). • **Curing:** The first three days bricks are spread in single layers on the floor for curing. Then from the 4th day, the bricks are kept in stacks. The bricks are cured for 14 – 21 days.
Production capacity	• Manual press: 1000 bricks per day. • Machine press: 4000 bricks per day..
Address/Contact	Mr. Gagan Sapian (+91-9910006899)

Thermal and physical properties	
Dry density, ρ (kg/m^3)	1630
Thermal conductivity, λ (W/m-K)	0.5883
Specific heat, C (KJ/kg-K)	0.9083
Water absorption, (%)	22
Compressive strength, σ (N/mm^2)	1.76

Datasheet 09

General information	
Sample type	Fly ash brick 
Sample number	FB04
Date of collection	March 6, 2019
Location	Najafgarh, Delhi
Raw material	Fly ash, Cement
Production processes	• **Mixture preparation:** Pan-mixer is used to mix raw material • **Shaping:** Bricks are shaped by a rotary-hydraulic power compacting machine and then cured by water**.**
Address/Contact	Moksh Enterprises Mr. Jaydev Mann (9868953455)

Thermal and physical properties	
Dry density, ρ (kg/m^3)	1299
Thermal conductivity, λ (W/m-K)	0.387
Specific heat, C (KJ/kg-K)	0.9240
Water absorption, (%)	27
Compressive strength, σ (N/mm^2)	11.44

Datasheet 10

General information	
Sample type	Extruded burnt-clay brick 
Sample number	RB05
Date of collection	February 19, 2019
Location	Dera Bassi, Punjab
Raw material	Excavated clay
Production processes	• **Clay preparation**: Mechanical (using earth excavator and pug mill) • **Shaping**: Bricks are shaped using extrusion machine. • **Drying**: Bricks are dried in a tunnel dryer • **Firing**: Bricks are fired in a tunnel kiln • **Fuel**: Petcoke
Fuel consumption	18-ton pet-coke per lakh bricks
Production capacity	Capacity of the extruder: 20,000 bricks per 8 hours
Address/Contact	Bharat bricks Mr. Kulbhushan, +91-9425052825

Thermal and physical properties	
Dry density, ρ (kg/m^3)	2028
Thermal conductivity, λ (W/m-K)	1.119
Specific heat, C (KJ/kg-K)	0.9552
Water absorption, (%)	10
Compressive strength, σ (N/mm^2)	54

Datasheet 11

General information	
Sample type	Hand-moulded burnt-clay brick 
Sample number	RB06
Date of collection	February 19, 2019
Location	Dera Bassi, Punjab
Raw material	Excavated clay
Production processes	• **Clay preparation**: Mechanical (using earth excavator and pug mill) • **Shaping**: Bricks are shaped using extrusion machine. • **Drying**: Bricks are dried in a tunnel dryer • **Firing**: Bricks are fired in a tunnel kiln • **Fuel**: Petcoke
Fuel consumption	12-ton pet-coke per lakh bricks
Production capacity	50,000 bricks per day
Address/Contact	Bharat bricks Mr. Kulbhushan, +91-9425052825

Thermal and physical properties	
Dry density, ρ (kg/m^3)	1887
Thermal conductivity, λ (W/m-K)	0.7645
Specific heat, C (KJ/kg-K)	0.9270
Water absorption, (%)	12
Compressive strength, σ (N/mm^2)	20.23

Datasheet 12

General information	
Sample type	Fly ash brick 
Sample number	FB05
Date of collection	February 19, 2019
Location	Near airport, Chandigarh
Raw material	Fly ash, cement
Address/Contact	Mr. Jaamavar (contractor), +91-9915068553

Thermal and physical properties	
Dry density, ρ (kg/m^3)	1807
Thermal conductivity, λ (W/m-K)	0.5042
Specific heat, C (KJ/kg-K)	0.9611
Water absorption, (%)	15
Compressive strength, σ (N/mm^2)	10.64

Datasheet 13

General information	
Sample type	Concrete brick 
Sample number	CB01
Date of collection	February 19, 2019
Location	Village Jhanjheri, Distt Mohali, Punjab
Raw material	**M10 concrete product**: 10mm aggregate, coarse sand & fly ash, and cement (1:3:6)
Production processes	Fully mechanized concrete manufacturing line (make: COLUMBIA)
Address/Contact	Ramjee concrete Pvt. Ltd., (http://www.ramjeeconcrete.com/index.html),

Thermal and physical properties	
Dry density, ρ (kg/m^3)	2122
Thermal conductivity, λ (W/m-K)	1.546
Specific heat, C (KJ/kg-K)	0.9200
Water absorption, (%)	7
Compressive strength, σ (N/mm^2)	29.6

Datasheet 14

General information	
Sample type	Fly ash brick 
Sample number	FB06
Date of collection	March 1, 2019
Location	Sabarmati, Ahmedabad, Gujarat
Raw material	Fly ash and cement
Production processes	• **Mixture preparation**: Pan-mixer is used to mix raw material • **Shaping**: Bricks are shaped by a vibro-hydraulic power compacting machine and then cured by water.
Address/Contact	Nisarg Prajapati (+91- 9898864332)

Thermal and physical properties	
Dry density, ρ (kg/m^3)	1543
Thermal conductivity, λ (W/m-K)	0.3594
Specific heat, C (KJ/kg-K)	0.9080
Water absorption, (%)	27
Compressive strength, σ (N/mm^2)	5.05

Datasheet 15

General information	
Sample type	Hand-moulded burnt-clay brick 
Sample number	RB07
Date of collection	March 1, 2019
Location	Moraiya, Ahmedabad, Gujarat
Raw material	Excavated clay
Production processes	• **Clay preparation**: Slurry preparation involves clay crushing (hammer mill + roller mill) + double shaft mixer • **Shaping**: Hand moulding • **Drying**: Natural drying • **Firing**: Bricks are fired in a fixed chimney Bull's trench kiln. • **Fuel**: Steam coal, internal fuel (biomass)
Address/Contact	Harihar Bricks Mr. Rounak Prajapati (+91- 9825087595)

Thermal and physical properties	
Dry density, ρ (kg/m^3)	1738
Thermal conductivity, λ (W/m-K)	0.5313
Specific heat, C (KJ/kg-K)	0.9604
Water absorption, (%)	16
Compressive strength, σ (N/mm^2)	7.21

Datasheet 16

General information	
Sample type	Machine-moulded burnt-clay brick 
Sample number	RB08
Date of collection	March 1, 2019
Location	Moraiya, Ahmedabad, Gujarat
Raw material	Excavated clay
Production processes	• **Clay preparation**: Slurry preparation involves clay crushing (hammer mill + roller mill) + double shaft mixer • **Shaping**: Hand moulding • **Drying**: Natural drying • **Firing**: Bricks are fired in a fixed chimney Bull's trench kiln. • **Fuel**: Steam coal, internal fuel (biomass)
Address/Contact	Harihar Bricks Mr. Rounak Prajapati (+91- 9825087595)

Thermal and physical properties	
Dry density, ρ (kg/m^3)	1737
Thermal conductivity, λ (W/m-K)	0.5051
Specific heat, C (KJ/kg-K)	0.9468
Water absorption, (%)	16
Compressive strength, σ (N/mm^2)	7.76

Datasheet 17

General information	
Sample type	Hand-moulded burnt-clay brick 
Sample number	RB09
Date of collection	March 6, 2019
Location	Bhor Taluka Pune, Maharashtra
Raw material	Excavated clay
Production processes	• **Firing**: Bricks are fired in a clamp. • **Fuel**: C-Grade Steam coal
Fuel consumption	10 ton per lakh bricks
Production capacity	Clamp size is 50,000 to 100,000 bricks per clamp, firing cycle is 15 days.
Address/Contact	Mr. Vijay Parinchekar

Thermal and physical properties	
Dry density, ρ (kg/m^3)	1604
Thermal conductivity, λ (W/m-K)	0.3876
Specific heat, C (KJ/kg-K)	0.9090
Water absorption, (%)	23
Compressive strength, σ (N/mm^2)	6.1

Datasheet 18

General information	
Sample type	Calcium silicate brick 
Sample number	CS01
Date of collection	March 6-8, 2019
Location	Vadhu Budruk, Pune, Maharashtra
Raw material	Fly ash, stone dust, and lime
Production processes	• **Mixture preparation**: 70% stone dust, 10% fly ash from Nasik and 20% lime is used. • **Shaping and curing:** Mechanized production line; consisting of pan-mixer, Hydraulic Power compacting machine and steam curing (autoclaves).
Address/Contact	C-Cure Building Products Ltd. Mr. Mayank Gupta, (+91-9823181060)

Thermal and physical properties	
Dry density, ρ (kg/m³)	2071
Thermal conductivity, λ (W/m-K)	0.7069
Specific heat, C (KJ/kg-K)	0.9692
Water absorption, (%)	12
Compressive strength, σ (N/mm²)	18.79

Datasheet 19

General information	
Sample type	Cellular light weight concrete block 
Sample number	CL01
Date of collection	March 6-8, 2019
Location	Kesanand, Pune, Maharashtra
Raw material	Fly ash, cement & foam
Production processes	• **Mixture preparation**: M20 grade (dry season): 550 kg Fly ash, 60 kg cement & foam • **Shaping and curing:** Semi-mechanized production line; consisting of pan-mixer, Rotary-Hydraulic Power compacting machine, foam generation & water curing.
Address/Contact	C-Cure Building Products Ltd. Mr. Mayank Gupta, (+91-9823181060)

Thermal and physical properties	
Dry density, ρ (kg/m^3)	693
Thermal conductivity, λ (W/m-K)	0.1932
Specific heat, C (KJ/kg-K)	0.9322
Water absorption, (%)	78
Compressive strength, σ (N/mm^2)	1.12

Datasheet 20

General information	
Sample type	Fly ash brick 
Sample number	FB07
Date of collection	March 6-8, 2019
Location	Mundhwa, Pune, Maharashtra
Raw material	Fly ash, cement, and stone dust
Production processes	• **Mixture preparation**: Pan-mixer is used to mix raw material (100kg fly ash + 400kg stone dust+ 50 kg cement) • **Shaping**: Bricks are shaped by a vibro-hydraulic power compacting machine and then cured by water.
Address/Contact	C-Cure Building Products Ltd. Mr. Mayank Gupta, (+91-9823181060)

Thermal and physical properties	
Dry density, ρ (kg/m^3)	2048
Thermal conductivity, λ (W/m-K)	0.67
Specific heat, C (KJ/kg-K)	0.9762
Water absorption, (%)	12
Compressive strength, σ (N/mm^2)	15.16

Datasheet 21

General information	
Sample type	Hand-moulded burnt-clay brick 
Sample number	RB10
Date of collection	March 14-15, 2019
Location	Pithampur Road, Indore, Madhya Pradesh
Raw material	Excavated clay
Production processes	• **Firing**: Bricks are fired in a clamp. • **Shaping**: Hand-moulding • **Drying**: Natural drying • **Fuel**: Chindwara coal and bottom ash (internal fuel)
Production capacity	• Produces 50 lakh bricks per season (6 months) • Clamp size of 3-4 lakh bricks per clamp, 2-month cycle
Address/Contact	Abhishek Bricks Mr. Abhishek Purohit, (+91-9425052825)

Thermal and physical properties	
Dry density, ρ (kg/m³)	1512
Thermal conductivity, λ (W/m-K)	0.4244
Specific heat, C (KJ/kg-K)	0.9265
Water absorption, (%)	26
Compressive strength, σ (N/mm²)	5.32

Datasheet 22

General information	
Sample type	Fly ash brick 
Sample number	FB08
Date of collection	March 14 –15, 2019
Location	Pithampur Road, Indore, Madhya Pradesh
Raw material	Fly ash, cement, lime, and stone dust
Production processes	• **Mixture preparation**: Pan-mixer is used to mix raw material (40% stone dust, 40% fly ash, 15% lime and 5% PPC cement) • **Shaping**: Bricks are shaped by a vibro-hydraulic power compacting machine and then cured by water.
Production capacity	Two fly ash brick manufacturing plants; produces 30 lakh bricks per plant per season
Address/Contact	Abhishek Bricks Mr. Abhishek Purohit, (+91-9425052825)

Thermal and physical properties	
Dry density, ρ (kg/m^3)	1682
Thermal conductivity, λ (W/m-K)	0.5172
Specific heat, C (KJ/kg-K)	0.9360
Water absorption, (%)	19
Compressive strength, σ (N/mm^2)	10.14

Datasheet 23

General information	
Sample type	Hand moulded burnt-clay brick 
Sample number	RB11
Date of collection	April 2-3, 2019
Location	Nagpur
Raw material	Excavated clay
Production processes	• **Firing**: Bricks are fired in a FCBTK. • **Shaping**: Hand-moulding • **Drying**: Natural drying • **Fuel**: Nagpur coal and pond ash (internal fuel: 60 v/v)
Fuel consumption	12 ton per lakh bricks
Production capacity	50,000 bricks per day
Address/Contact	Mr Vinu Paul (+91-9822224122)

Thermal and physical properties	
Dry density, ρ (kg/m^3)	1447
Thermal conductivity, λ (W/m-K)	0.5016
Specific heat, C (KJ/kg-K)	0.9366
Water absorption, (%)	24
Compressive strength, σ (N/mm^2)	10.01

Datasheet 24

General information	
Sample type	Fly ash brick 
Sample number	FB09
Date of collection	April 2–3, 2019
Location	Nagpur
Raw material	Fly ash, cement, aggregate, and stone dust
Production processes	• **Mixture preparation**: Pan-mixer is used to mix raw material (470 kg stone dust, 200 kg fly ash, 100 kg aggregate and 30 kg OPC grade cement) • **Shaping**: Bricks are shaped by a vibro-hydraulic power compacting machine and then cured by water.
Production capacity	50,000 bricks per 8 hours
Address/Contact	Mr Vinu Paul (+91-9822224122)

Thermal and physical properties	
Dry density, ρ (kg/m^3)	1989
Thermal conductivity, λ (W/m-K)	0.6502
Specific heat, C (KJ/kg-K)	0.9300
Water absorption, (%)	13
Compressive strength, σ (N/mm^2)	8.87

Datasheet 25

General information	
Sample type	AAC block 
Sample number	AB01
Date of collection	April 2–3, 2019
Location	Village Zullar, P.O. - Wadoda, Nagpur
Raw material	Fly ash, cement, lime, and gypsum
Production processes	• **Mixture preparation**: Pan-mixer is used to mix raw material (60-70% fly ash, ~10-15% lime, ~10-15% cement, gypsum) • **Shaping**: Bricks are shaped by a vibro-hydraulic power compacting machine and then cured by water.
Address/Contact	Shreeji Blocks Pvt. Ltd. Mr. V Bhaskar Rao, (+91-7030963942)

Thermal and physical properties	
Dry density, ρ (kg/m^3)	608
Thermal conductivity, λ (W/m-K)	0.1669
Specific heat, C (KJ/kg-K)	0.8755
Water absorption, (%)	72
Compressive strength, σ (N/mm^2)	2.7

Datasheet 26

General information	
Sample type	Extruded burnt-clay brick 
Sample number	RB12
Date of collection	April 11, 2019
Location	Anekkal, Karnataka
Raw material	Excavated clay
Production processes	Extruded bricks fired in FCBTK

Thermal and physical properties	
Dry density, ρ (kg/m^3)	1975
Thermal conductivity, λ (W/m-K)	0.7969
Specific heat, C (KJ/kg-K)	928.1
Water absorption, (%)	12
Compressive strength, σ (N/mm^2)	26.83

Datasheet 27

General information	
Sample type	Solid burnt clay brick (soft mud) 
Sample number	RB13
Date of collection	April 11, 2019
Location	Anekkal, Karnataka
Raw material	Excavated clay
Production processes	• **Firing**: Bricks are fired in a FCBTK. • **Shaping**: Bricks are moulded by De-boer Damle soft mud moulding machine • **Drying**: Natural drying • **Fuel**: Chanderpur coal
Fuel consumption	16 ton per lakh bricks
Production capacity	- 35,000 soft mud capacity - 20,000 per day production capacity
Address/Contact	Sudarshan Bricks Chickahagadi village, Kasaba Hobli, Hoskote Post, Anekal taluk, Chikka Hagade, Bangalore. Mr. Sampangirama Reddy (+91-9558378293)

Thermal and physical properties	
Dry density, ρ (kg/m^3)	1807
Thermal conductivity, λ (W/m-K)	0.5893
Specific heat, C (KJ/kg-K)	0.9348
Water absorption, (%)	17
Compressive strength, σ (N/mm^2)	13.48

Datasheet 28

General information	
Sample type	Compressed stabilized earth block 
Sample number	EB02
Date of collection	April 10, 2019
Location	Kengeri, Bangalore
Raw material	Soil, fine dust and, cement
Production processes	• **Mixture preparation**: Cement 9% + Soil + fine dust. The soil is tested and based on the tests the composition is estimated • **Shaping**: Bricks are pressed into shape by a manual press machine
Production capacity	1000 – 1200 bricks per day
Address/Contact	Manjunath Ubalmath, manjunath.u@goodearth.org.in (+919591989248)

Thermal and physical properties	
Dry density, ρ (kg/m^3)	1773
Thermal conductivity, λ (W/m-K)	0.7493
Specific heat, C (KJ/kg-K)	0.9348
Water absorption, (%)	16
Compressive strength, σ (N/mm^2)	13.05

Datasheet 29

General information	
Sample type	Concrete block 
Sample number	CC01
Date of collection	April 12, 2019
Location	HSR layour, Bengaluru
Raw material	Stone dust, cement, and aggregate (M10 concrete mix)
Production processes	• **Mixture preparation**: Pan-mixer is used to mix raw material (Cement + stone dust + 6mm aggregate) • **Shaping**: Bricks are shaped by a double-vibro-hydraulic power compacting machine and then cured by water.
Production capacity	12,000 blocks per week
Address/Contact	Venus Concrete Products Rajesh V. (+91-9611554455) Production units = 1) Bommanahalli 2) Anekal

Thermal and physical properties	
Dry density, ρ (kg/m^3)	2032
Thermal conductivity, λ (W/m-K)	0.8071
Specific heat, C (KJ/kg-K)	0.9128
Water absorption, (%)	9
Compressive strength, σ (N/mm^2)	10.04

Datasheet 30

General information	
Sample type	Hand-moulded Solid burnt clay brick 
Sample number	RB14
Date of collection	April 16, 2019
Location	Guntur, Andhra Pradesh
Raw material	Excavated clay
Production processes	Bricks are fired in a clamp.
Address/Contact	DNDL constructions Suresh Babu (+91-9440250446)

Thermal and physical properties	
Dry density, ρ (kg/m^3)	1503
Thermal conductivity, λ (W/m-K)	0.4162
Specific heat, C (KJ/kg-K)	0.9359
Water absorption, (%)	26
Compressive strength, σ (N/mm^2)	4.88

Datasheet 31

General information	
Sample type	Concrete block 
Sample number	CC02
Date of collection	April 16, 2019
Location	Lam, Vijaywada, Andhra Pradesh
Raw material	Stone dust, cement, lime, fly ash and coarse aggregate
Address/Contact	Sri Manikanta Fly ash Bricks Industry-(099482 35778)

Thermal and physical properties	
Dry density, ρ (kg/m^3)	1961
Thermal conductivity, λ (W/m-K)	0.6601
Specific heat, C (KJ/kg-K)	0.9289
Water absorption, (%)	13
Compressive strength, σ (N/mm^2)	6.8

Datasheet 32

General information	
Sample type	Hand-moulded Solid burnt clay brick 
Sample number	RB15
Date of collection	April 17, 2019
Location	Karimnagar, Telangana
Raw material	Excavated clay, fly ash, bottom ash and paddy husk

Production processes	• Bricks are fired in a clamp.
	• Government supplied clay excavated from lakes
	• Internal fuel: NTPC Ramagundam fly ash + paddy husk + boiler ash
	• Coal: Singareni mines
	• Composition
	  ▪ NTPC ash: 28 tractors (3 ton/ tractor) = 84 ton
	  ▪ Clay: 24 tractors (3 ton/tractor) = 72 ton
	  ▪ Husk: 6 ton
	  ▪ Boiler ash: 6 ton
	  ▪ ~ 54% ash w/w

Fuel consumption	Coal: 17 ton per two lakh bricks
Production capacity	• 2 lakh bricks per clamp (15 days cycle) • 30 lakh bricks per year
Address/Contact	NBC Brick kiln - Mr. Nageshwar Rao – (+91-9440501259) Tata Trust – Ms. Sarah Khosla – (+91-8280569700)

Thermal and physical properties	
Dry density, ρ (kg/m^3)	1264
Thermal conductivity, λ (W/m-K)	0.3757
Specific heat, C (KJ/kg-K)	0.9278
Water absorption, (%)	32
Compressive strength, σ (N/mm^2)	4.16

Datasheet 33

General information	
Sample type	Solid burnt clay brick 
Sample number	RB16
Date of collection	April 22, 2019
Location	Tirunelveli, Tamil Nadu
Raw material	Excavated clay
Production processes	• Bricks are fired in FCBTK • Firewood is used as fuel for firing • Bricks are shaped by: o Soft mud moulding machine (locally made): 10,000 bricks per day o Extruder (make: Vigo): 20,000 bricks per day
Production capacity	• 30,000 bricks per day; 8 months' kiln operation
Address/Contact	Mr. K Rathna Shekhar Shri Annamalayar Brick Works (+91-9344034133)

Thermal and physical properties	
Dry density, ρ (kg/m^3)	1657
Thermal conductivity, λ (W/m-K)	0.4206
Specific heat, C (KJ/kg-K)	940.4
Water absorption, (%)	19
Compressive strength, σ (N/mm^2)	7.51

Datasheet 34

General information	
Sample type	Solid burnt clay brick 
Sample number	RB17
Date of collection	April 23, 2019
Location	Madurai, Tamil Nadu
Raw material	Excavated clay
Production processes	• Bricks are fired in FCBTK • Fuels used for firing are Indonesian coal and wood pieces • Bricks are shaped by soft mud moulding machine (capacity of 30,000 per day).
Production capacity	• 40,000 bricks per day
Address/Contact	Mr. Zackari Yasin Bricks (+91-9786010740)

Thermal and physical properties	
Dry density, ρ (kg/m^3)	1648
Thermal conductivity, λ (W/m-K)	0.4061
Specific heat, C (KJ/kg-K)	0.9275
Water absorption, (%)	20
Compressive strength, σ (N/mm^2)	5.71

Datasheet 35

General information	
Sample type	Solid burnt clay brick 
Sample number	RB18
Date of collection	April 23, 2019
Location	Madurai, Tamil Nadu
Raw material	Excavated clay
Production processes	• Bricks are fired in FCBTK • Fuels used for firing are Indonesian coal and wood pieces • Bricks are shaped by extrusion machine (locally made having capacity of 25,000 per day).
Production capacity	• 40,000 bricks per day
Address/Contact	Mr. Zackari Yasin Bricks (+91-9786010740)

Thermal and physical properties	
Dry density, ρ (kg/m^3)	1895
Thermal conductivity, λ (W/m-K)	0.5817
Specific heat, C (KJ/kg-K)	0.9243
Water absorption, (%)	14
Compressive strength, σ (N/mm^2)	19.82

Datasheet 36

General information	
Sample type	Fly ash brick 
Sample number	FB10
Date of collection	April 23, 2019
Location	Thirupuvanam, Madurai, Tamil Nadu
Raw material	Fly ash, pond ash, stone dust, granite dust and cement
Production processes	• **Mixture preparation**: Pan-mixer is used to mix raw material (20 kg Fly ash + 20 kg Pond ash + 30 kg stone dust + 30 kg Granite dust + 4 kg Cement) • **Shaping**: Bricks are shaped by a vibro-hydraulic power compacting machine and then cured by water.
Address/Contact	P K Bricks (+91-9443461272)

Thermal and physical properties	
Dry density, ρ (kg/m^3)	1722
Thermal conductivity, λ (W/m-K)	0.4989
Specific heat, C (KJ/kg-K)	0.9256
Water absorption, (%)	20
Compressive strength, σ (N/mm^2)	3.6

Datasheet 37

General information	
Sample type	Solid burnt clay bricks 
Sample number	RB19
Date of collection	April 25, 2019
Location	Chinnathadagam, Coimbatore, Tamil Nadu
Raw material	Excavated clay
Production processes	• Bricks are fired in FCBTK • Fuels used for firing is imported coal (Tuticorin port) • Clay preparation is mechanized • Bricks are shaped by extrusion machine (capacity: 50,000 bricks per day) having automatic wire-cutting table.
Production capacity	• 50,000 bricks per day
Address/Contact	Mini Chamber bricks Mr. V. Sampathkumar (+91-9363122555)

Thermal and physical properties	
Dry density, ρ (kg/m^3)	1958
Thermal conductivity, λ (W/m-K)	0.6469
Specific heat, C (KJ/kg-K)	0.9472
Water absorption, (%)	13
Compressive strength, σ (N/mm^2)	10.79

Datasheet 38

General information	
Sample type	Solid burnt clay bricks 
Sample number	RB20
Date of collection	June 13, 2019
Location	Yamunanagar, Haryana
Raw material	Excavated clay
Production processes	• Bricks are fired in IDZK • Fuels used for firing is USA coal • Clay preparation is mechanized • Bricks are shaped by hand moulding
Fuel consumption	Coal consumption: 9 Ton (when pond ash is used as internal fuel)
Production capacity	• 60,000 bricks per day
Address/Contact	Harpreet Bricks Mr. Harpreet (+91-9416117084)

Thermal and physical properties	
Dry density, ρ (kg/m^3)	1780
Thermal conductivity, λ (W/m-K)	0.5532
Specific heat, C (KJ/kg-K)	0.9529
Water absorption, (%)	15
Compressive strength, σ (N/mm^2)	18.68

Datasheet 39

General information	
Sample type	Solid burnt clay bricks 
Sample number	RB21
Date of collection	June 18, 2019
Location	Baraut (Baghpat), UP
Raw material	Excavated clay
Production processes	• Bricks are fired in NDZK • Fuels used for firing is USA coal. Sugar mill waste, saw dust or sugar mill fly ash is used as internal fuel. • Clay preparation is mechanized • Bricks are shaped by hand moulding
Fuel consumption	Coal consumption: 9 Ton (when internal fuel is used); 10 Ton (when no internal fuel is used)
Production capacity	• 25,000 – 30,000 bricks per day
Address/Contact	Brahma Bricks Mr. Ramesh (+91-9999009307)

Thermal and physical properties	
Dry density, ρ (kg/m^3)	1716
Thermal conductivity, λ (W/m-K)	0.5415
Specific heat, C (KJ/kg-K)	0.9231
Water absorption, (%)	17
Compressive strength, σ (N/mm^2)	17.8

Datasheet 40

General information	
Sample type	AAC block 
Sample number	AB02
Date of collection	July 3, 2019
Location	Matanhail (Jhajhar), Haryana
Raw material	Pond ash/Fly ash, Aluminium powder, Lime, Sodium dichromate, Detergent, Plaster of Paris, Cement, and Water
Production processes	• Pond/Fly ash from power plant is made into slurry. • Moulds are made by mixing Slurry with Aluminium powder + Lime + Sodium dichromate + Detergent + Plaster of Paris + Cement + Water • Moulds are heated in Autoclave pipes by Steam (P = 12.5 kgf/cm^2) in a 12-hour cycle.
Production capacity	200 Moulds per day (Mould volume = 4.9 m^3)
Address/Contact	Magicrete Building Solutions Pvt. Ltd. Mr. Sidharth Bansal (+91-9769443244)

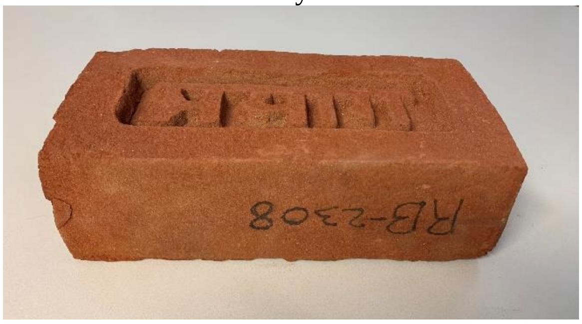
Thermal and physical properties	
Dry density, ρ (kg/m^3)	623
Thermal conductivity, λ (W/m-K)	0.1879
Specific heat, C (KJ/kg-K)	0.8310
Water absorption, (%)	73
Compressive strength, σ (N/mm^2)	3.4

Datasheet 41

General information	
Sample type	Soft moulded Burnt-clay brick 
Sample number	RB22
Date of collection	September 9, 2019
Location	Varanasi, Uttar Pradesh
Raw material	Excavated clay, sugar cane waste
Production processes	• **Clay preparation**: Mechanical (using earth excavator and pug mill) • **Shaping**: Soft mud moulding • **Drying**: Artificial drying using fans • **Firing**: Bricks are fired in a natural draught Zigzag kiln • **Fuel**: Coal, Sawdust
Production capacity	35 lakh bricks per year
Address/Contact	PCPPL, Hariharpur, Varanasi Mr. O P Badlani (+91-9935111095)

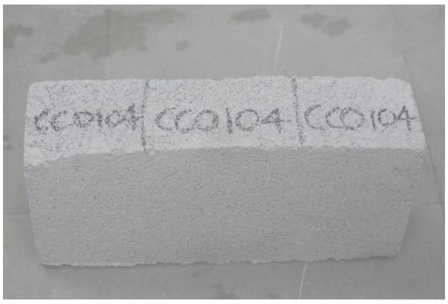
Thermal and physical properties	
Dry density, ρ (kg/m^3)	1798
Thermal conductivity, λ (W/m-K)	0.6414
Specific heat, C (KJ/kg-K)	0.9185
Water absorption, (%)	14
Compressive strength, σ (N/mm^2)	26.17

Datasheet 42

General information	
Sample type	Hand moulded Burnt-clay brick 
Sample number	RB23
Date of collection	September 9, 2019
Location	Varanasi, Uttar Pradesh
Raw material	Excavated clay, sugar cane waste
Production processes	• **Clay preparation**: Mechanical (using earth excavator and pugmill) • **Shaping**: Hand moulding • **Drying**: Natural Drying • **Firing**: Bricks are fired in a natural draught Zigzag kiln • **Fuel**: Coal, Sawdust
Production capacity	24 lakh bricks per year
Address/Contact	PCPPL, Ganeshpur, Varanasi Mr. O P Badlani (+91-9935111095)

Thermal and physical properties	
Dry density, ρ (kg/m^3)	1819
Thermal conductivity, λ (W/m-K)	0.7383
Specific heat, C (KJ/kg-K)	0.9786
Water absorption, (%)	13
Compressive strength, σ (N/mm^2)	25.8

Datasheet 43

General information	
Sample type	Concrete Block 
Sample number	CC01
Date of collection	22 July 2020
Location	**Adibatla, Hyderabad, Telangana**
Raw material	Sand, stone chips, cement
Production processes	• Raw materials are mixed with water, and are moulded in the form of blocks by hydraulic press • The moulded blocks are cured with water for strength
Address/Contact	Govardhana Reddy, Venkata Shyam Enterprise, Adibutla, Hyderabad

Thermal and physical properties	
Dry density, ρ (kg/m^3)	2015
Thermal conductivity, λ (W/m-K)	NA
Specific heat, C (KJ/kg-K)	0.886
Water absorption, (%)	9
Compressive strength, σ (N/mm^2)	6.6

Datasheet 44

General information	
Sample type	Concrete Block 
Sample number	CC02
Date of collection	10 September 2020
Location	Tirupati, Andhra Pradesh
Raw material	Stone dust, flyash, cement
Production processes	• Raw materials are mixed with water, and are moulded in the form of blocks by hydraulic press • The moulded blocks are cured with water for strength
Address/Contact	Sai Babu C/o K V Chaudhary

Thermal and physical properties	
Dry density, ρ (kg/m^3)	2117
Thermal conductivity, λ (W/m-K)	NA
Specific heat, C (KJ/kg-K)	0.907
Water absorption, (%)	9
Compressive strength, σ (N/mm^2)	10.2

Datasheet 45

General information	
Sample type	Concrete Block 
Sample number	CC03
Date of collection	24 August 2020
Location	Bagodra, Gujarat
Raw material	Aggregates (6 & 10 mm), flyash, cement
Production processes	• Raw materials are mixed (dry mix), and are moulded in the form of blocks by vibration compactor • The moulded blocks are cured with water for strength
Address/Contact	Ace Infracon Products

Thermal and physical properties	
Dry density, ρ (kg/m^3)	2092
Thermal conductivity, λ (W/m-K)	0.6992
Specific heat, C (KJ/kg-K)	0.868
Water absorption, (%)	11
Compressive strength, σ (N/mm^2)	11.59

Datasheet 46

General information	
Sample type	Demolition Waste Brick 
Sample number	CD01
Date of collection	22 July 2020
Location	Ahmedabad, Gujarat
Raw material	Cement, lime, crushed C&D waste
Production processes	• Raw materials are mixed with water, and are moulded in the form of blocks by hydraulic press • The moulded blocks are cured with water for strength
Address/Contact	Keyur Sarda, Kesarjan Building Center Pvt. Ltd., Ahmedabad

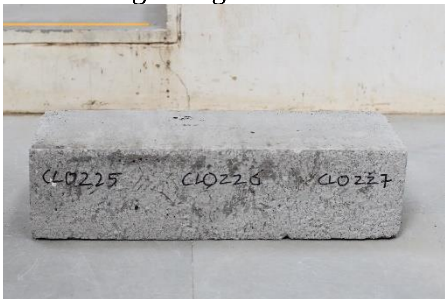
Thermal and physical properties	
Dry density, ρ (kg/m^3)	1537
Thermal conductivity, λ (W/m-K)	0.5432
Specific heat, C (KJ/kg-K)	0.956
Water absorption, (%)	23
Compressive strength, σ (N/mm^2)	6.63

Datasheet 47

General information	
Sample type	Cellular Lightweight Concrete Block 
Sample number	CL01
Date of collection	27 July 2020
Location	Vishakhapatnam, Andhra Pradesh
Raw material	Flyash, cement, foaming agent
Production processes	• Raw materials mixed with water and foam are poured into mould boxes. • After 24 hours, blocks are taken out of moulds and water cured.
Address/Contact	Aditya CLC ECO Blocks, Plot # 194 & 195, A.I.E, Visakhapatnam – 530 044

Thermal and physical properties	
Dry density, ρ (kg/m^3)	760
Thermal conductivity, λ (W/m-K)	0.2023
Specific heat, C (KJ/kg-K)	1.048
Water absorption, (%)	37
Compressive strength, σ (N/mm^2)	2.63

Datasheet 48

General information	
Sample type	Cellular Lightweight Concrete Block 
Sample number	CL02
Date of collection	07 October 2020
Location	Vadodara, Gujarat
Raw material	Flyash, cement, foaming agent
Production processes	• Raw materials mixed with water and foam are poured into mould boxes. • After 24 hours, blocks are taken out of moulds and water cured.
Address/Contact	FFC

Thermal and physical properties	
Dry density, ρ (kg/m^3)	744
Thermal conductivity, λ (W/m-K)	0.2063
Specific heat, C (KJ/kg-K)	0.892
Water absorption, (%)	44
Compressive strength, σ (N/mm^2)	2.86

Datasheet 49

General information	
Sample type	Compressed Stabilized Earth Block 
Sample number	EB01
Date of collection	04 September 2020
Location	Puducherry
Raw material	Sand, soil, cement
Production processes	• Raw materials are mixed with water, and are moulded in the form of blocks by manual press • The moulded blocks are cured with for strength
Address/Contact	Auroville Earth Institute

Thermal and physical properties	
Dry density, ρ (kg/m^3)	1993
Thermal conductivity, λ (W/m-K)	0.9669
Specific heat, C (KJ/kg-K)	1.040
Water absorption, (%)	12
Compressive strength, σ (N/mm^2)	2.91

Datasheet 50

General information	
Sample type	Expanded clay aggregate brick 
Sample number	EC01
Date of collection	06 August 2020
Location	Rajkot, Gujarat
Raw material	Light weight fired clay aggregates, cement, sand
Production processes	• Light weight fired-clay aggregates were mixed with cement and sand • They were moulded in the form of blocks and cured
Address/Contact	Nexus Buildcon Solutions Off N. H. 8A (Bamanbor-Morvi), Mesariya Road, Rangapar Village, Tal. Wakaner, Dist. Rajkot, Gujarat, India

Thermal and physical properties	
Dry density, ρ (kg/m³)	613*
Thermal conductivity, λ (W/m-K)	0.1856
Specific heat, C (KJ/kg-K)	1.032
Water absorption, (%)	30
Compressive strength, σ (N/mm²)	2.77

Datasheet 51

General information	
Sample type	Fly ash brick 
Sample number	FB01
Date of collection	16 July 2020
Location	Hyderabad, Telangana
Raw material	Flyash, cement, stone dust
Production processes	• Raw materials are mixed with water, and are moulded in the form of blocks by hydraulic press • The moulded blocks are cured with water for strength
Address/Contact	Mr Vikram, KSP Industries, Hyderabad

Thermal and physical properties	
Dry density, ρ (kg/m^3)	1878
Thermal conductivity, λ (W/m-K)	1.0490
Specific heat, C (KJ/kg-K)	0.918
Water absorption, (%)	10
Compressive strength, σ (N/mm^2)	15.72

Datasheet 52

General information	
Sample type	Fly ash brick 
Sample number	FB02
Date of collection	10 September 2020
Location	Tirupati, Andhra Pradesh
Raw material	Flyash, Dust, Aggregate(6mm), Cement, Gypsum
Production processes	• Raw materials are mixed with water, and are moulded in the form of blocks by hydraulic press • The moulded blocks are cured with water for strength
Address/Contact	Sai Babu C/o K V Chaudhary

Thermal and physical properties	
Dry density, ρ (kg/m^3)	1779
Thermal conductivity, λ (W/m-K)	0.8401
Specific heat, C (KJ/kg-K)	0.935
Water absorption, (%)	15
Compressive strength, σ (N/mm^2)	18.72

Datasheet 53

General information	
Sample type	Fly ash brick 
Sample number	FB03
Date of collection	22 August 2020
Location	Ahmedabad, Gujarat
Raw material	Fly Ash, Stone Dust, Lime, Cement
Production processes	• Raw materials are mixed with water, and are moulded in the form of blocks by hydraulic press • The moulded blocks are cured with water for strength
Address/Contact	Ace Infracon Products

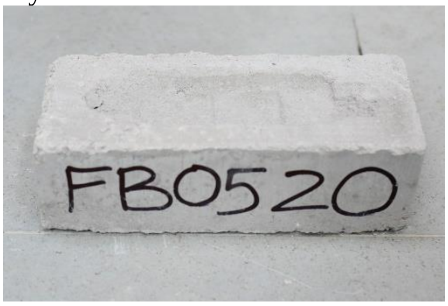
Thermal and physical properties	
Dry density, ρ (kg/m^3)	1716
Thermal conductivity, λ (W/m-K)	0.5610
Specific heat, C (KJ/kg-K)	0.891
Water absorption, (%)	17
Compressive strength, σ (N/mm^2)	12.07

Datasheet 54

General information	
Sample type	Fly ash brick 
Sample number	FB04
Date of collection	16 September 2020
Location	Kota, Rajasthan
Raw material	Fly Ash, Grit Stone, Lime, Gypsum
Production processes	• Raw materials are mixed with water, and are moulded in the form of blocks by hydraulic press • The moulded blocks are cured with water for strength
Address/Contact	OASIS Enterprises

Thermal and physical properties	
Dry density, ρ (kg/m^3)	1606
Thermal conductivity, λ (W/m-K)	0.6731
Specific heat, C (KJ/kg-K)	0.954
Water absorption, (%)	19
Compressive strength, σ (N/mm^2)	9.97

Datasheet 55

General information	
Sample type	Fly ash brick 
Sample number	FB05
Date of collection	16 September 2020
Location	Kota, Rajasthan
Raw material	Fly Ash, Stone Crusher Dust, Lime, Plaster of Paris
Production processes	• Raw materials are mixed with water, and are moulded in the form of blocks by hydraulic press • The moulded blocks are cured with water for strength
Address/Contact	Bairwa Ash Bricks Store

Thermal and physical properties	
Dry density, ρ (kg/m^3)	1627
Thermal conductivity, λ (W/m-K)	0.6911
Specific heat, C (KJ/kg-K)	0.954
Water absorption, (%)	18
Compressive strength, σ (N/mm^2)	8.57

Datasheet 56

General information	
Sample type	Fly Ash Brick 
Sample number	FB06
Date of collection	24 September, 2020
Location	Jaipur, Rajasthan
Raw material	Fly Ash, Stone Dust, Cement
Production processes	• Raw materials are mixed with water, and are moulded in the form of blocks by hydraulic press • The moulded blocks are cured with water for strength
Address/Contact	Premraj Khatri Building

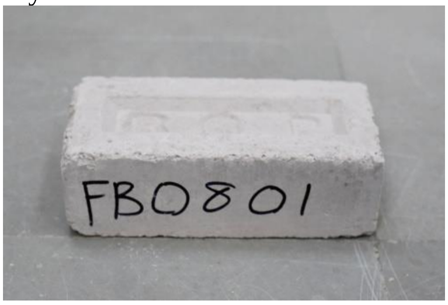
Thermal and physical properties	
Dry density, ρ (kg/m^3)	1774
Thermal conductivity, λ (W/m-K)	0.9735
Specific heat, C (KJ/kg-K)	0.879
Water absorption, (%)	15
Compressive strength, σ (N/mm^2)	10.33

Datasheet 57

General information	
Sample type	Fly Ash Brick 
Sample number	FB07
Date of collection	24 September 2020
Location	Jaipur, Rajasthan
Raw material	Fly Ash, Stone Dust, Lime
Production processes	• Raw materials are mixed with water, and are moulded in the form of blocks by hydraulic press • The moulded blocks are cured with water for strength
Address/Contact	Bharat Bricks Industries

Thermal and physical properties	
Dry density, ρ (kg/m^3)	1734
Thermal conductivity, λ (W/m-K)	0.7901
Specific heat, C (KJ/kg-K)	0.972
Water absorption, (%)	18
Compressive strength, σ (N/mm^2)	8.75

Datasheet 58

General information	
Sample type	Fly Ash Brick 
Sample number	FB08
Date of collection	05 November, 2020
Location	Bikaner, Rajasthan
Raw material	Fly Ash, Stone Crusher Dust (6 mm), Lime, Plaster of Paris, River sand
Production processes	• Raw materials are mixed with water, and are moulded in the form of blocks by hydraulic press • The moulded blocks are cured with water for strength
Address/Contact	Ramseetu Green Products

Thermal and physical properties	
Dry density, ρ (kg/m³)	1694
Thermal conductivity, λ (W/m-K)	0.7521
Specific heat, C (KJ/kg-K)	0.646
Water absorption, (%)	20
Compressive strength, σ (N/mm²)	15.16

Datasheet 59

General information	
Sample type	Hand moulded burnt clay brick 
Sample number	RB01
Date of collection	17 July, 2020
Location	Baghpat, Delhi-NCR
Raw material	Excavated clay, waste from sugar industry
Production processes	• Raw material mixed with water are moulded manually and dried • The dried bricks are fired in zigzag kiln using coal fuel
Address/Contact	Mr. Ramesh Kumar, KBC Bricks, Baghpat, Uttar Pradesh

Thermal and physical properties	
Dry density, ρ (kg/m^3)	1801
Thermal conductivity, λ (W/m-K)	0.5715
Specific heat, C (KJ/kg-K)	0.927
Water absorption, (%)	12
Compressive strength, σ (N/mm^2)	21.76

Datasheet 60

General information	
Sample type	Machine made burnt clay brick 
Sample number	RB02
Date of collection	09 October 2020
Location	Tirupati, Andhra Pradesh
Raw material	Clay, flyash, stone dust
Production processes	• Raw material mixed with water are moulded with machine and dried • The dried bricks are fired in FCBTK kiln using coal fuel
Address/Contact	K. V. Chaudhary

Thermal and physical properties	
Dry density, ρ (kg/m^3)	1723.0
Thermal conductivity, λ (W/m-K)	0.5802
Specific heat, C (KJ/kg-K)	0.891
Water absorption, (%)	12
Compressive strength, σ (N/mm^2)	5.84

Datasheet 61

General information	
Sample type	Hand moulded burnt clay brick 
Sample number	RB03
Date of collection	09 October 2020
Location	Tirupati, Andhra Pradesh
Raw material	Clay, flyash, stone dust
Production processes	• Raw material mixed with water are moulded manually and dried • The dried bricks are fired in FCBTK kiln using coal fuel
Address/Contact	KV Chaudhary

Thermal and physical properties	
Dry density, ρ (kg/m^3)	1493.0
Thermal conductivity, λ (W/m-K)	0.4131
Specific heat, C (KJ/kg-K)	0.910
Water absorption, (%)	20
Compressive strength, σ (N/mm^2)	5.22

Datasheet 62

General information	
Sample type	Machine moulded burnt clay brick 
Sample number	SB01
Date of collection	22 July 2020
Location	Ahmedabad, Gujarat
Raw material	Burnt clay brick waste, cement, lime
Production processes	• Broken burnt-clay bricks (waste) sourced from brick kilns are crushed and mixed with cement, lime and water, and moulded with hydraulic press • Moulded bricks are cured with water
Address/Contact	Keyur Sarda, Kesarjan Building Center Pvt. Ltd., Ahmedabad

Thermal and physical properties	
Dry density, ρ (kg/m^3)	1423
Thermal conductivity, λ (W/m-K)	0.4558
Specific heat, C (KJ/kg-K)	0.5249
Water absorption, (%)	28
Compressive strength, σ (N/mm^2)	5.96

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Advancing Building Energy Efficiency in India

Thermal Performance of Walling Material and Wall Technology

Part-II: Derivation of Thermal Transmittance Values of Wall Assemblies and Walling Technologies

October 2022

Supported by

Project By

Construction Agency

Advancing Building Energy Efficiency in India

Thermal performance of Walling Materials and Wall Technology

Part II: Derivation of Thermal Transmittance Values of Wall Assemblies and Walling Technologies

October 2022

Shakti Sustainable Energy Foundation

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Disclaimer

The views/analysis expressed in this document do not necessarily reflect the views of the funding agencies. The funding agencies also does not guarantee the accuracy of any data included in this publication nor does it accept any responsibility for the consequences of its use.

Phases I and II were supported by SSEF and included the testing of following technologies:

1. Rat-trap bond wall
2. Light Gauge framed steel structure with EPS
3. Light Gauge framed steel structure with PPGI Sheet
4. Reinforced EPS core Panel system
5. Glass fibre reinforced Gypsum Panel -Unfilled
6. Glass fibre reinforced Gypsum Panel -with RCC & non-structural filling
7. Glass fibre reinforced Gypsum Panel -with partial RCC filling
8. Burnt clay brick wall
9. Structural stay-in-place formwork system with Insulated panel
10. Bamboo Crete
11. Wattle and Daub
12. Stabilized Adobe Wall
13. Laterite Block Wall
14. Unstabilized Adobe Wall
15. Compressed Stabilized Earth Block (CSEB) wall
16. Unstabilized Compressed Earth Block (CEB) Wall
17. AAC Block with Perlite-based cement plaster
18. Unstabilized Rammed Earth
19. Stabilized Rammed Earth
20. AAC Block wall with cement mortar and cement plaster
21. AAC Block wall with lime mortar and lime plaster
22. Burnt Clay Brick wall with lime mortar and lime plaster
23. Limestone block wall with cement mortar and cement plaster
24. Limestone block wall with lime mortar and lime plaster

Phase III was supported by NVF and included the testing of following technologies:

1. Hollow clay brick (100 mm thickness) with cement plaster
2. Hollow clay brick (100 mm thickness) with cement plaster and XPS
3. Hollow clay brick (200 mm thickness) with rockwool and cement plaster
4. Hollow clay brick (200 mm thickness) with cement plaster
5. Hollow clay brick (200 mm thickness) with cement plaster and XPS
6. RCC Wall (100 mm Thickness)
7. RCC Wall (100 mm Thickness) with EPS
8. RCC Wall (100 mm Thickness) with Styrofoam on both sides
9. RCC Wall (100 mm Thickness) with PVC Panels on both sides
10. RCC Wall (100 mm Thickness) with EPS Board on one side and PVC Panels on both sides

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ABBREVIATIONS

ASTM	American Society for Testing and Materials
BIS	Bureau of Indian Standards
BMTPC	Building Materials and Technology Promotion Council
CARBSE	Centre for Research in Building Science and Energy
CEPT	Centre for Environmental Planning and Technology
CP	Cement particles
CRDF	CEPT Research and Development Foundation
EPS	Expanded Polystyrene
GFRG	Glass Fibre Reinforced Gypsum Panel
GHB	Guarded Hot Box
GI	Galvanised Iron
GKSPL	Greentech Knowledge Solutions Pvt. Ltd
HVAC	Heating Ventilation and Air-Conditioning
LGFSS	Light Gauge Framed Steel Structure

MoHUA	Ministry of Housing and Urban Affairs, Government of India
PACS	Performance Appraisal Certification Scheme
PCM	Phase Change Materials
PMAY	Pradhan Mantri Awas Yojna
PPGI	Pre-painted Galvanised Iron
RCC	Reinforced Concrete Cement
SDC	Swiss Agency for Development and Cooperation
TSM	Technology Sub-Mission
XPS	Extruded Polystyrene
RH	Relative Humidity
U-Value	Thermal transmittance value (W/m^2 K)

1. Introduction

The rising demand of affordable housing within urban cities in India is a constant challenge. As a result, emerging construction systems and walling technologies are being developed to improve the cost and speed dynamics involved in construction that uses conventional methods and materials. However, considering climate change and associated events, the focus on thermal performance of all categories of walling technologies is justified. This report submitted by CRDF, CEPT University aims to facilitate knowledge regarding thermal performance evaluation of wall construction technologies through the derivation of their U-values, using its state-of-the-art laboratory facilities. To validate their U-value test results for a dependable reference in sustainable building practices, the research activity protocol has been listed in Figure 1. This database has been envisaged to facilitate efficient and sustainable affordable housing construction This research activity tests thirty-four wall assemblies that may fall in one of the following categories:

- Conventional Walling Technologies: This includes business-as-usual wall assemblies such as burnt clay brick, RCC walls, etc can be used as reference baselines.
- Alternative Walling Technologies: This category includes region-specific walling assemblies used in vernacular architecture such as bamboo-crete, rammed earth walls, etc
- Emerging Walling Technologies: This category refers to industrialized walling technologies, systems, and/ or products such as reinforced EPS core panel systems.

1. Assessment of research lab capacity and capability	• Name and role of the lab, its testing instruments and standards.
2. Identification of approved and employed walling technologies	• Identification of government body for walling technology certification as a validated source for sample selection.
2.1 Sampling criteria	• Setting criteria aiming to cover the most trending technologies first, enabling possible interventions at the earliest.
2.2 Selected walling technologies	• List, literature and drawings of the selected walling technologies confirming with the stated criteria to support their characterization.
3 Procurement of the samples	• Approaching certified manufacturers to supply, confirming with the required test sample size.
4. Testing Procedure	• Use of the testing instrument and exceptional measures for this research project.
5 Derivation of U-Values of the samples	• Database of thermal transmittance values (U-values) and their comparative evaluation based on their thermal performance.

Figure 1: Project outline and research activity protocol.

2. Assessment of Research Lab capacity and capabilities

2.1 CARBSE, CEPT University, Ahmedabad

Centre for Advanced Research in Building Science and Energy (CARBSE), under CRDF, CEPT University, Ahmedabad has characterized and tested the walling technology samples procured from different manufacturers using Guarded Hot Box (GHB), as per ASTM C 1363.

2.2 Guarded Hot Box (GHB)

A Guarded Hot Box is used to test the thermal performance of non-homogenous specimens, such as complex wall assemblies, cavity walls, ventilated shaded wall assembly or walls with phase change materials (PCM). It determines the amount of heat transfer through a given material or assembly of various materials. This is done by controlling the temperature on both sides of the material and minimizing the extraneous heat transfers that takes place through material other than the given one; which can be used to determine the thermal transmittance of a homogenous as well as a non-homogenous specimen and can test a specimen with a maximum thickness of 350mm. The metering chamber, as seen in Figure 2, is cooled using a chiller and the guard chamber is maintained at the same temperature using an HVAC system. The climatic chamber is maintained at higher temperatures using electric coils. Surface, water and air temperature sensors are placed for temperature control along with relative humidity (RH), pressure, and air velocity sensors placed at equal distances. The GHB used for testing is custom made as per ASTM C1363. The range of measurement is 0.1 to 5 W/m^{2}k and the specimen size must have a maximum width of 980 mm, length of 980 mm and thickness up to 300 mm (CBERD, 2014). Figure 3 is a photograph showing the assembly of GHB at CARBSE. The testing procedure is further elaborated in Section 3 of this report.

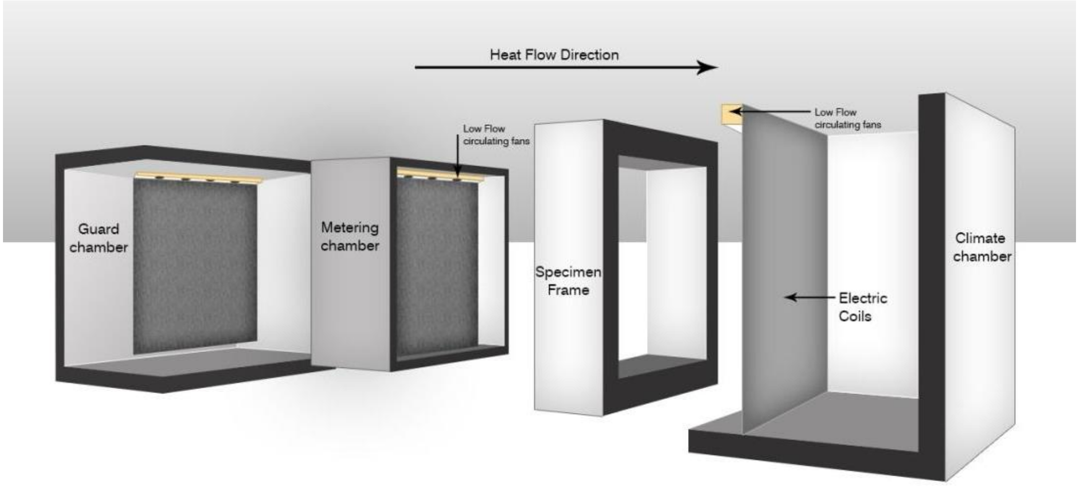


Figure 2: Exploded view of the Guarded Hot-Box apparatus.

Figure 3: Photographs of the metering chamber attached to the specimen frame and the entire assembly of GHB opened up and closed.

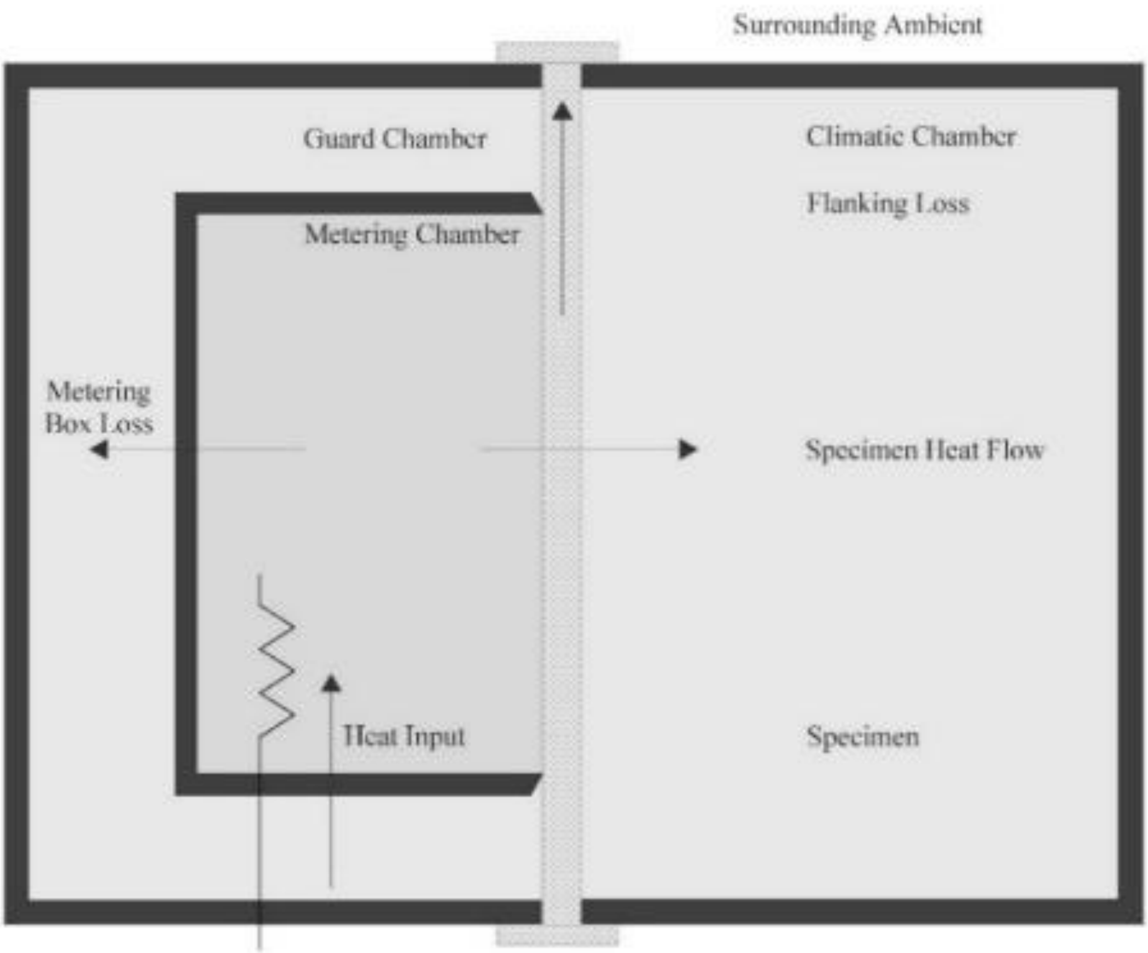


Figure 4: Sectional illustration of the Guarded Hot Box (GHB) apparatus

3. Testing Procedure

This section introduces the standard testing procedure followed for the testing of masonry based walls and BMTPC certified walls.

3.1 General Procedure

The guarded hot box (GHB) apparatus is traditionally recognized as the only absolute method for thermal conductivity measurement in a steady state for homogeneous and non-homogeneous materials.

To determine the net energy flow through the specimen, a five sided metering box is placed with the open side against the warm face of the test panel. Apparently, if there is no net energy exchange across the walls other than that of the metering box, and only negligible flanking loss around the specimen, the heat input from the fan and heaters, minus any cooling coil energy extraction from the metering box, would be considered a measure of the energy flux through the metered area of the specimen.

Since it is not practically possible to have the condition mentioned above, the GHB apparatus is designed to obtain an accurate measure of the net sample heat flow. Here, the net energy transfer through the specimen is determined from net measured energy input to the metering chamber, rectifying the losses through the chamber walls and flanking loss for the specimen at the perimeter of the metering area. The heat loss rate through the metering chamber walls is curbed by using highly insulated walls and controlling the surrounding ambient temperature, or by using a temperature controlled guard chamber.

That portion of the specimen outside the boundary of the metering area or the specimen frame, exposed to the guarding space temperature, constitutes a passive guard to minimize the flanking heat flow in the test panel near the perimeter of the metering area.

The basic hot box apparatus can be assembled in a wide variety of sizes, orientations, and designs. There are two primary design configurations. The first is the guarded hot box used for the testing, that has a controlled "guard" chamber surrounding the metering box. An example of this configuration is presented in Figure 4 (ASTM, n.d.).

3.2 GHB testing procedure for masonry walls

The two masonry walls, rat-trap bond wall and brick wall, were constructed directly into the specimen frame of GHB as explained in Annexure 1. The walls were plastered on both sides using 1:4 external cement plaster and were allowed to dry. Thermal imaging camera was used to check for presence of moisture ensuring dryness and then the specimen frame was assembled back into the GHB as seen in Figure 5.

3.3 GHB Testing Procedure of BMTPC Certified Walls:

The manufactured BMTPC certified wall samples were procured in the required size of 980 mm x 980 mm to be fixed directly into the GHB specimen frame. Any gaps between the sample and the specimen frame were further sealed using XPS insulation strips and finally sealed using a silicone sealant as seen in Figure 5 and Figure 6.

Figure 5: Photographs showing thermal imaging (left) and testing of Rattrap bond wall assembly in GHB

Figure 6: Photographs showing sealing procedure with XPS (left) and silicone sealant (right) to avoid heat transfer through gaps

4. Identification of Walling Technologies

The identification and selection of walling assemblies varied in the three phases and was performed in consultation with GKSPL. Products/wall technologies suitable for external wall applications (i.e. exposed to outer environment) were identified.

4.1 Sampling criteria

To comply with the main objective of this research project, the wall assemblies certified by the Building Materials and Technology Promotion Council (BMTPC), and approved by Pradhan Mantri Awas Yojana (PMAY) are identified in the first category. PMAY is an initiative by the Government of India, started in 2015, to aid rehabilitation of existing slum dwellers and provide a pucca house to every household by 2022. BMTPC is an autonomous organization under the Ministry of Housing and Urban Affairs (MoHUA), Government of India. It has been mandated to identify and certify innovative materials and technologies under its Performance Appraisal Certification Scheme (PACS) and evaluate their application in mass housing. The first set of 8 such technologies was published as Compendium of Prospective Emerging Technologies for Mass Housing in 2015, and its second edition with 16 new construction systems was published in April 2017. The third edition that released in September 2018 has 24 new technologies. Figure 7 shows the cover pages of all the 3 compendiums released so far.

Furthermore, the Annual Report 2017-2018 published by Ministry of housing and urban affairs, under Pradhan Mantri Awas Yojana- Housing For All (Urban) also lists out the same 16 new technologies certified under the 2nd edition of BMTPC Compendium. These technologies have been earmarked to be adopted under the PMAY mission as on 31.11.2017, as seen in Figure 8 (MOHUA, 2017).

Figure 7: Cover pages of 3 different editions of BMTPC Compendium of Prospective Emerging Technologies for Mass Housing.
Source: (BMTPC, n.d.-a)

To cover the most trending technologies such as industrially manufactured and/or pre-fabricated walling technologies in phase I, enabling possible interventions at the earliest, the following criteria was set:

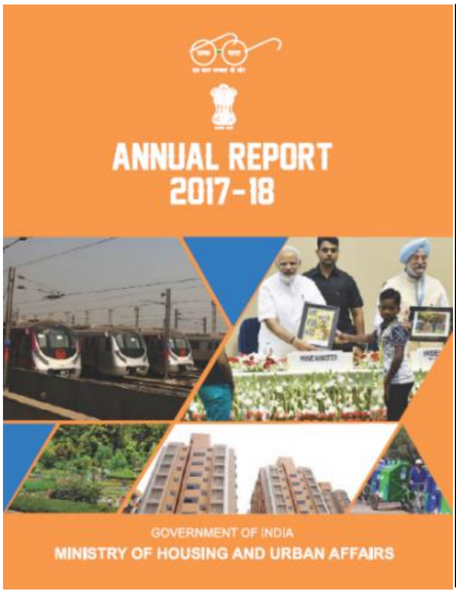
1. Availability of Performance Appraisal Certificate (PAC) for the technology.
2. The wall assembly is non-homogenous by nature
3. Availability of the product for procurement from the manufacturers.
4. The willingness of the manufacturers to provide the required wall samples of the size 980mm x 980mm to fit in the GHB instrument's specimen frame for testing.
5. The ability to alter the sample in-situ, in the size of 980mm x 980mm, without changing the properties of the sample in case the manufacturer does not agree to supply the required size of the sample.

The second category of wall assemblies were identified based on the following criteria:

1. Wall construction must be masonry based.
2. Traditional walling techniques that are currently being used in vernacular and contemporary-green building practices in India must be selected.
3. Technology must be selected based on its feasibility of the sample construction to fit in the testing apparatus frame without any changes in its properties or the regional way of construction.

The third category of wall assemblies were identified based on the following criteria:

1. Varying wall thickness and/or insulating material for the same wall construction technique
2. Technology must be selected based on its feasibility of the sample construction to fit in the testing apparatus frame while ensuring inclusion of walling technologies obtained as a result of emerging construction techniques such as those implemented in LHP projects.



Progress of Technology Sub-Mission (TSM) as on 31.11.2017

- **Till date 16 new technologies have been earmarked to be adopted under the PMAY(U) mission:**
  - Formwork Systems
    1. Monolithic Concrete Construction using Plastic/Aluminium formwork
    2. Modular Tunnel form
    3. Sismo Building Technology
  - Precast Sandwich Panel Systems
    4. Advanced Building System - EMMEDUE
    5. Rapid Panels
    6. Reinforced EPS Core Panel System
    7. Quick Build 3D Panels
    8. Concrete wall Panel System
    9. Glass Fibre Reinforced Gypsum (GFRG) Panel System
  - Light Gauge Steel Structural Systems
    10. Light Gauge Steel Framed Structure (LGSFS)
    11. Light Gauge Steel Framed Structure with Infill Concrete Panels (LGSFS-ICP)
  - Steel Structural Systems
    12. Factory Made Fast Track Building System
    13. Speed Floor System
  - Precast Concrete Construction Systems
    14. Waffle-Crete Building System
    15. Precast Large Concrete Panel System
    16. Industrialized 3-S system using cellular light weight concrete slabs & precast columns

Figure 8: Cover page of the latest Annual report by MoHUA (left) and the list of 16 technologies assigned to be adopted for PMAY mission (right)
Source: (MOHUA, 2017)

4.2 Selected Walling Technologies

Non-homogeneous and low-cost masonry construction techniques/technologies, such as Rattrap bond wall and the standard brick wall, were tested along with selected walling technologies to understand the comparative assessment between the conventional and the advanced technologies. The selected wall assemblies were also referred to Greentech Knowledge Solutions Pvt. Ltd (GKSPL) for additional guidance on understanding the properties of similar technologies. Technologies selected for testing are specified in Table 1. Refer Annexures 1 and 2 for more information on the assemblies.

Table 1: List of wall construction selected for U value testing.

Phase	S/N	Technologies
I	1	Rattrap bond wall
	2	Light Gauge framed steel structure with EPS
	3	Light Gauge framed steel structure with PPGI Sheet
	4	Reinforced EPS core Panel system
	5	Glass fibre reinforced Gypsum Panel - Unfilled
	6	Glass fibre reinforced Gypsum Panel - with RCC and non-structural filling
	7	Glass fibre reinforced Gypsum Panel - with RCC filling
	8	Structural stay-in-place formwork system (Coffor) – Insulated panel
	9	Standard Brick Wall
II	10	Bamboo Crete
	11	Wattle and Daub
	12	Stabilized Adobe
	13	Laterite Block Wall
	14	Unstabilized Adobe
	15	CSEB
	16	Unstabilized CEB
	17	AAC Block Wall with Icyplast Cement Plaster
	18	Unstabilized Rammed Earth
	19	Stabilized Rammed Earth
	20	AAC Block Wall with Cement Mortar and Cement Plaster
	21	AAC Block Wall with Lime mortar and Lime Plaster
	22	Burnt Clay Brick with Lime Mortar and Lime Plaster
	23	Limestone with Lime Mortar and Lime Plaster
	24	Limestone with Cement Mortar and Cement Plaster
III	25	Hollow Clay Brick (100mm thick) with Cement Plaster
	26	Hollow Clay Brick (100mm thick) with Cement Plaster and XPS
	27	Hollow Clay Brick (200mm thick) with Rockwool and Cement Plaster
	28	Hollow Clay Brick (200mm thick) with Cement Plaster
	29	Hollow Clay Brick (200mm thick) with Cement Plaster and XPS
	30	RCC Wall (100 mm thick)
	31	RCC Wall with EPS
	32	RCC Wall with Styrofoam on both sides
	33	RCC Wall with PVC panels on both sides
	34	RCC Wall with PVC panels on both side and EPS board
		Total- 34

4.3 Procurement of Samples

Samples of the walling construction technologies were procured only from the manufacturers holding a Performance Appraisal Certificate (PAC) issued by BMTPC. (BMTPC, n.d.-b). Drawings and details, as seen in Annexure 2, necessary for this process were shared with the manufacturers with reference to the information available in the PAC documents and respective websites. Table 2 shows manufacturer information and the PAC document numbers assigned to the selected wall technologies. Correspondence was maintained until the sample was received at the lab.

The traditional walling systems needed to be constructed in the prevalent vernacular way of construction, employing skilled artisans with expert guidance for results that can be applied. Thus, the execution services were rendered by MAT – Lab, a firm specialized in bamboo & earth construction, construction innovations, artisan training and R&D (hereinafter referred to as Second Party). All the traditional walling samples required regional craftsmen to construct the framework or make the masonry units regionally using their nearest locally available materials. The same samples were constructed or finished directly into the 980 mm x 980 mm specimen frame of GHB as explained in Annexure 1. The in-situ finishing required cement or mud plastering, masonry of the masonry units, curing and drying. Table 3 shows more information of the second party and its list of services for this project. Drawings and details as seen in Annexure 1 and 2, necessary for this process were shared by the Thus, second party. Correspondence was maintained until the sample was secured into the apparatus.

Table 2: List of walling technologies selected along with source region, manufacturer information, and PAC number.

Sr No.	Wall Technology/ Masonry	Manufacturer	Location	PAC No
1	Rattrap bond wall	-	Ahmedabad, Gujarat	-
2	Light Gauge framed steel structure with EPS	M/s JB Fabinfra Pvt. Ltd	Bhikaji Cama Place, New Delhi	1014-S/2014
3	Light Gauge framed steel structure with PPGI Sheet	M/s JB Fabinfra Pvt. Ltd	Bhikaji Cama Place, New Delhi	1014-S/2014
4	Reinforced EPS core Panel system	M/s Jindal Steel & Power Ltd	Angul, Odisha	1020-S/2015
5	Glass fibre reinforced Gypsum Panel - Unfilled	M/s FACT – RCF Building Products Ltd. (FRBL)	Cochin, Kerala	1009-S/2012
6	Glass fibre reinforced Gypsum Panel -with RCC and non-structural filling	M/s FACT – RCF Building Products Ltd. (FRBL)	Cochin, Kerala	1009-S/2012

7	Glass fibre reinforced Gypsum Panel -with RCC filling	M/s FACT – RCF Building Products Ltd. (FRBL)	Cochin, Kerala	1009-S/2012
8	Structural stay-in-place formwork system (Coffor) – Insulated panel	M/s Coffor Construction Technology Pvt. Ltd.,	Vadodara, Gujarat	1035-S/ 2018
9	Brick Wall	-	Ahmedabad, Gujarat	-`
10	Bamboo Crete	-	Maroli, Navsari, Gujarat	-
11	Wattle and Daub	-	Dang, Gujarat	-
12	Stabilized Adobe	-	North Gujarat	-
13	Laterite Block Wall	-	South Maharashtra	-
14	Unstabilized Adobe	-	Bhal/Bhavnagar/Vedgaon, Gujarat	-
15	CSEB	-	North Gujarat	-
16	Unstabilized CEB	-	North Gujarat/ Aravalli	-
17	AAC Block Wall with Perlite-based Cement Plaster	-	Ahmedabad, Gujarat	-
18	Unstabilized Rammed Earth	-	Dhrangadhra, Gujarat	-
19	Stabilized Rammed Earth	-	North Gujarat	-
20	AAC Block Wall with Cement Mortar and Cement Plaster	-	Ahmedabad, Gujarat	-
21	AAC Block Wall with Lime mortar and Lime Plaster	-	Ahmedabad, Gujarat	-
22	Burnt Clay Brick with Lime Mortar and Lime Plaster	-	Ahmedabad, Gujarat	-
23	Limestone with Lime Mortar and Lime Plaster	-	Junagadh, Gujarat	-
24	Limestone with Cement Mortar and Cement Plaster	-	Junagadh, Gujarat	-
25	Hollow Clay Brick (100mm thk) with Cement Plaster	Weinerberger India Pvt. Ltd.	Bengaluru, Karnataka	

26	Hollow Clay Brick (100mm thk) with Cement Plaster and XPS	Weinerberger India Pvt. Ltd.	Bengaluru, Karnataka XPS- Ahmedabad, Gujarat	-
27	Hollow Clay Brick (200mm thk) with Rockwool and Cement Plaster	Weinerberger India Pvt. Ltd.	Bengaluru, Karnataka Rockwool- Ahmedabad, Gujarat	-
28	Hollow Clay Brick (200mm thk) with Cement Plaster	Weinerberger India Pvt. Ltd.	Bengaluru, Karnataka	-
29	Hollow Clay Brick (200mm thk) with Cement Plaster and XPS	Weinerberger India Pvt. Ltd.	Bengaluru, Karnataka XPS- Ahmedabad, Gujarat	-
30	RCC Wall	-	Ahmedabad, Gujarat	-
31	RCC Wall with EPS	-	Ahmedabad, Gujarat	-
32	RCC Wall with Styrofoam on both sides	-	Ahmedabad, Gujarat	-
33	RCC Wall with PVC panels on both sides	-	Ahmedabad, Gujarat	-
34	RCC Wall with PVC panels on both side and EPS board	-	Ahmedabad, Gujarat	-

Table 3: Second Party information and its list of services

Name of the Second Party	MAT – Lab Surat, Gujarat, India
Technical coordinator	Mr. Manu Narendran
Project Name	Execution of traditional Walling System
List of services for this project	1. Execution of all the traditional walling systems. 2. Procuring local materials and co-ordinating with the artisans. 3. Transportation of the materials, artisans, and assembly supervisor. 4. Photographic and written documentation of the construction process. 5. Drawings of all the wall samples with material specifications and construction details. 6. Provide technical facilitation related to securing the walling system into the apparatus.

5. Results

Table 4 shows the U-values obtained for all twenty-four tested wall assemblies and Figure 9 shows evaluation of the thermal performances of the same.

Table 4: U-value database of all selected walling assemblies and technologies.

S. No.	Wall types	Thickness (mm)	U value (W/m^2K)
	Phase- I		
1	Rattrap bond wall	250	2.11
2	Light Gauge framed steel structure with EPS	136	1.37
3	Light Gauge framed steel structure with PPGI Sheet	150	2.12
4	Reinforced EPS core Panel system	150	0.56
5	Glass fibre reinforced Gypsum Panel - Unfilled	124	2.06
6	Glass fibre reinforced Gypsum Panel - with RCC & non-structural filling	124	2.12
7	Glass fibre reinforced Gypsum Panel - with partial RCC filling	124	2.13
8	Brick Wall	250	2.41
9	Structural stay-in-place formwork system (Coffor) – Insulated panel	230	0.44
	Phase- II		
10	Bamboo Crete	65	2.71
11	Wattle and Daub	45	3.61
12	Stabilized Adobe	230	2.11
13	Laterite Block Wall	205	2.17
14	Unstabilized Adobe	230	2.05
15	Compressed Stabilized Earth Block wall (CSEB)	230	2.79
16	Unstabilized Compressed Earth Block Wall	230	2.74

17	AAC Block Wall with Perlite-based Cement Plaster	230	0.76
18	Unstabilized Rammed Earth	230	2.13
19	Stabilized Rammed Earth	230	2.09
20	AAC Block Wall with Cement Mortar and Cement Plaster	230	0.78
21	AAC Block Wall with Lime mortar and Lime Plaster	220	0.82
22	Burnt Clay Brick with Lime Mortar and Lime Plaster	250	2.31
23	Limestone with Lime Mortar and Lime Plaster	224	2.84
24	Limestone with Cement Mortar and Cement Plaster	230	2.82
	Phase-III		
25	Hollow Clay Brick (100mm thick) with Cement Plaster	130	2.71
26	Hollow Clay Brick (100mm thick) with Cement Plaster and XPS	158	0.89
27	Hollow Clay Brick (200mm thick) with Rockwool and Cement Plaster	230	1.28
28	Hollow Clay Brick (200mm thick) with Cement Plaster	230	1.83
29	Hollow Clay Brick (200mm thick) with Cement Plaster and XPS	258	0.75
30	RCC Wall (100 mm thick)	100	3.59
31	RCC Wall with EPS	153	0.58
32	RCC Wall with Styrofoam on both sides	154	0.65
33	RCC Wall with PVC panels on both sides	112	2.62
34	RCC Wall with PVC panels on both side and EPS board	165	0.52

Note: The thermal conductivity of burnt clay brick used for the rat-trap bond wall was tested using the *Thermal Constants Analyser* as 0.5187 W/mK and brick wall as 0.5286 W/mK.

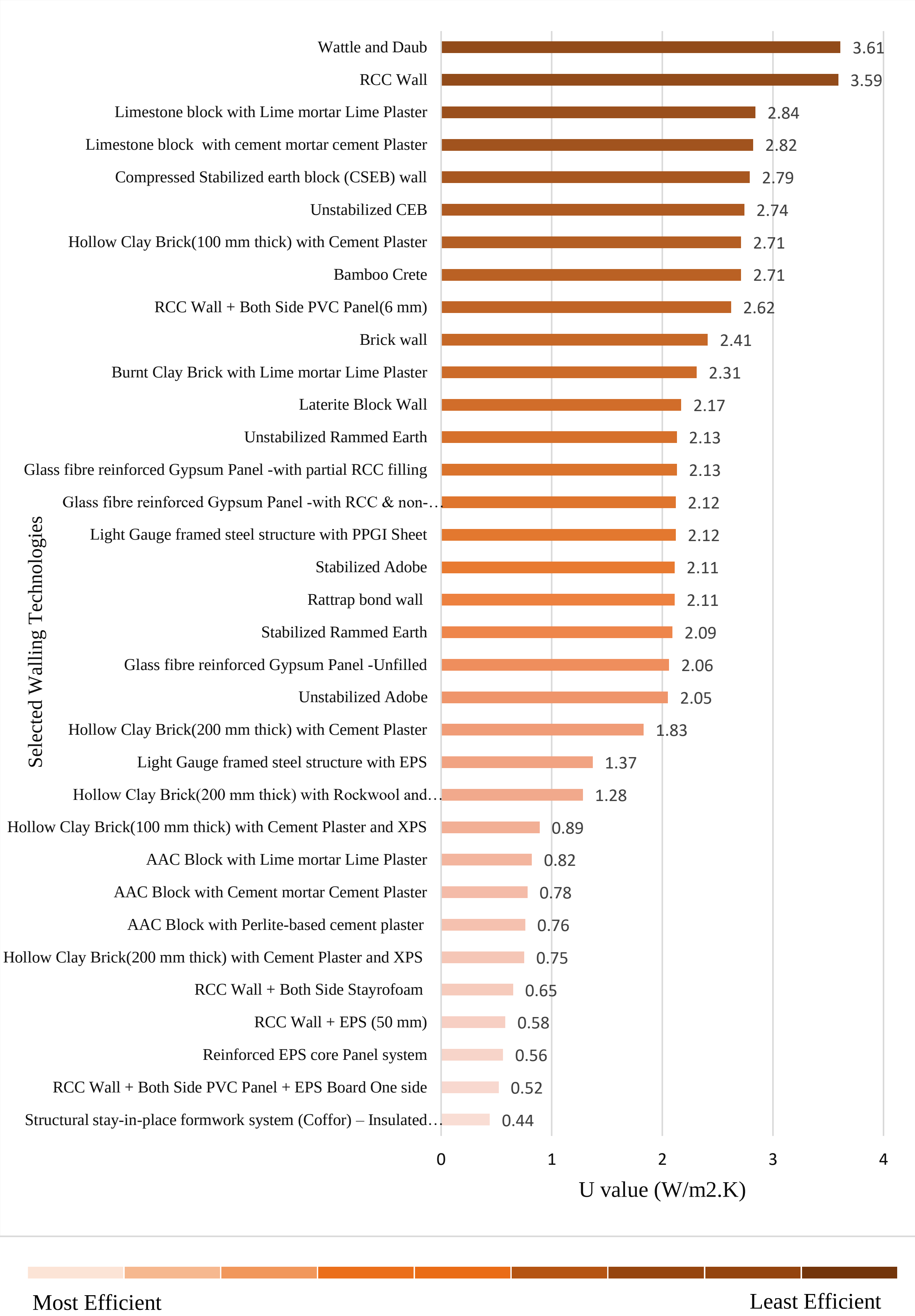


Figure 9: Thermal performance evaluation of the selected wall assemblies.

6. Annexures

Annexure I: Summary of the Selected Walling Technologies

This section is an elaboration on the types of wall samples procured and tested for thermal performance using GHB.

1. Rat-Trap Bond Wall

Rat-trap bond is a variation in wall masonry and was introduced to India by Architect Laurie Baker as a cost effective method of wall construction. Construction of external walls using this method is known to consume 35 % less number of standard burnt-clay bricks and 50 % less cement mortar when compared to conventional brick wall constructions such as English bond and Flemish bond. This construction is also known to provide better thermal insulation due to the presence of air cavities (Swiss Agency for Development and Cooperation SDC, n.d.). According to a study on the influence of masonry bond patterns on indoor thermal performance, rat-trap bond wall was observed to have maintained the lowest indoor temperature over a 24-hr period, with inner and outer surface temperature readings taken during bright and sunny days of March-April (Jayasinghe, 2016).

The walls are typically 230 mm thick and the bricks are laid as shown in Figure 11 with different brick faces (Shiners and Rowlocks) to form a cavity unlike conventional bricklaying (Stretchers and headers). The Rat trap bond is an external walling technique and is recommended for load-bearing buildings up to 3 storeys and as filler walls for buildings with concrete columns and beams (Swiss Agency for Development and Cooperation SDC, n.d.).

For the purpose of this research, the 230 mm thick rat-trap bond wall was constructed within the specimen frame of GHB using locally available burnt clay bricks from Ahmedabad as shown in Figure 12. The illustration in plan and elevation is available in Annexure 2.

Figure 10: Photograph of a housing project by Laurie Baker employing rat-trap bond wall assembly.

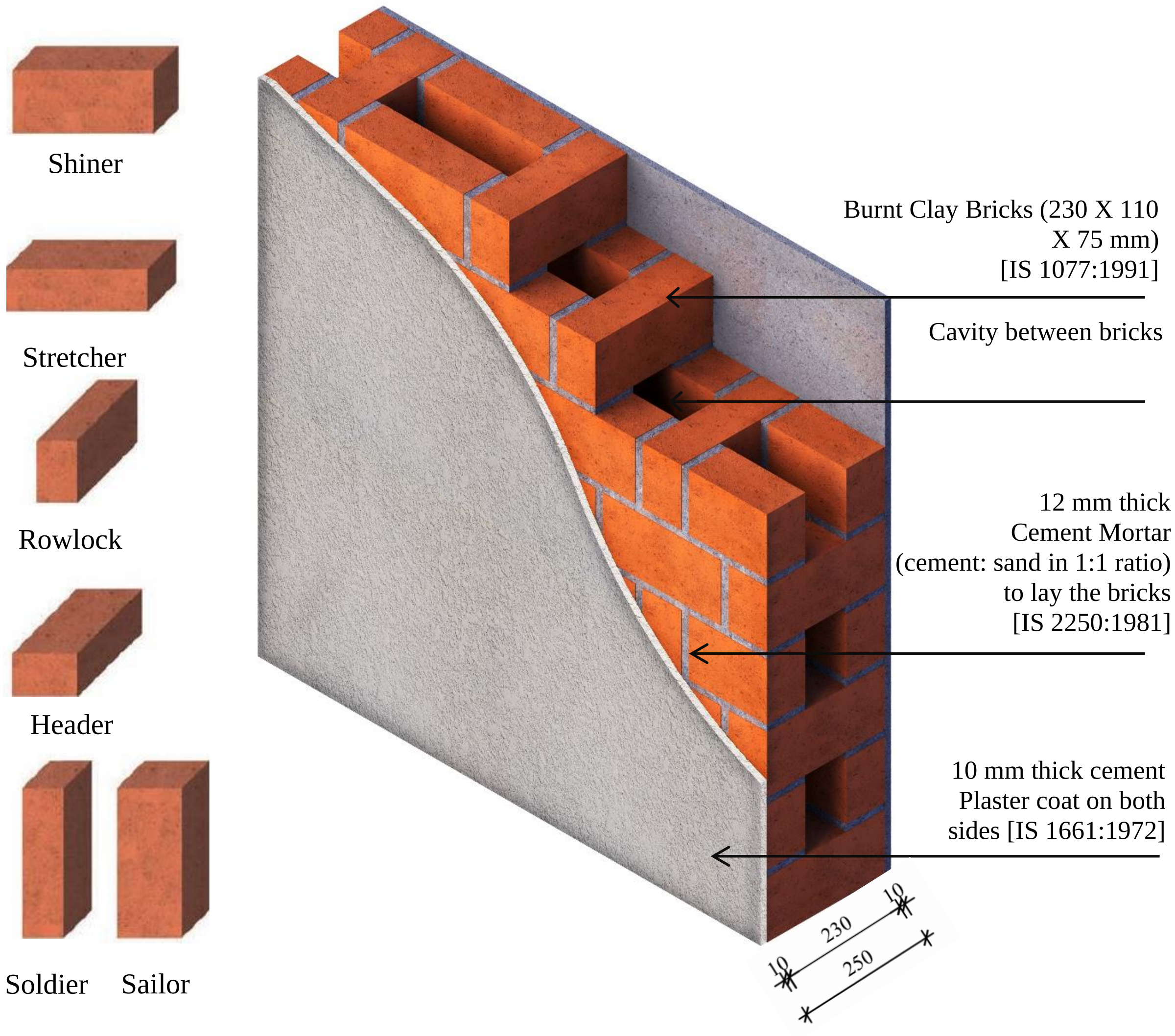


Figure 11: Different brick faces used in wall construction (left) and 3d illustration of a typical Rat-trap bond Wall (right).

Figure 12: Photographs showing the construction of Rat-trap bond wall within the specimen frame of GHB.

2. Light Gauge Framed Steel Structure (LGFSS)

Light Gauge Framed Steel Structure (LGFSS) is a technology consisting of light gauge steel components that form a structural framework that are manufactured using cold forming methods. These panels are assembled on-site with the help of screws and bolts to form walls, floors and roof of buildings, as shown inFigure 13. This technology has been certified to be adopted for both multi-storied and low-rise residential buildings (BMTPC, 2014). Once the structure is fixed, the panels are lined with an external layer of insulation material and Cement Particle (CP) board or dry mix shotcrete. For the purpose of this research, amongst the different types of wall panels available, the following two types, as seen in Figure 14 and Figure 15 were selected for testing based on its usage for external applications and their non-homogeneous nature.

a. LGFSS with Expanded Polystyrene (EPS) and Guniting/Shotcrete

This LGFSS wall type has a GI steel stud frame and layers of Gypsum board as its internal layers and EPS board and shotcrete as its external layers, as illustrated in Figure 16 shows the test sample acquired from the manufacturer mentioned in Table 2 and fixed into the GHB specimen frame. The illustration in plan and elevation is available in Annexure 2.

b. LGFSS with PPGL sheet

This LGFSS wall type has a GI steel stud frame and layers of Gypsum board as its internal layer, vapor barrier and pre-painted galvanized iron sheet (PPGI) as external layers. Figure 17 shows the test sample acquired from the manufacturer mentioned in Table 2 and fixed into the GHB specimen frame. The illustration in plan and elevation is available in Annexure 2.

Figure 13: Photograph showing walls and floor plates of LGFSS assembled at a site.

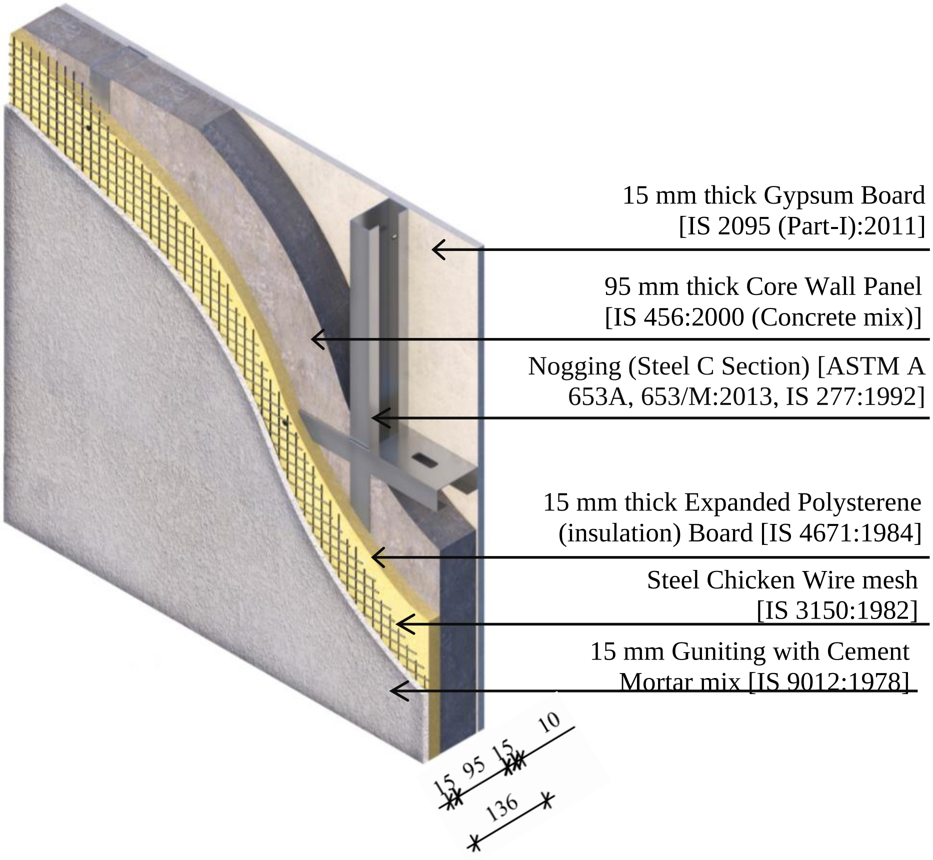


Figure 14: 3D illustration of LGFSS - EPS with specifications

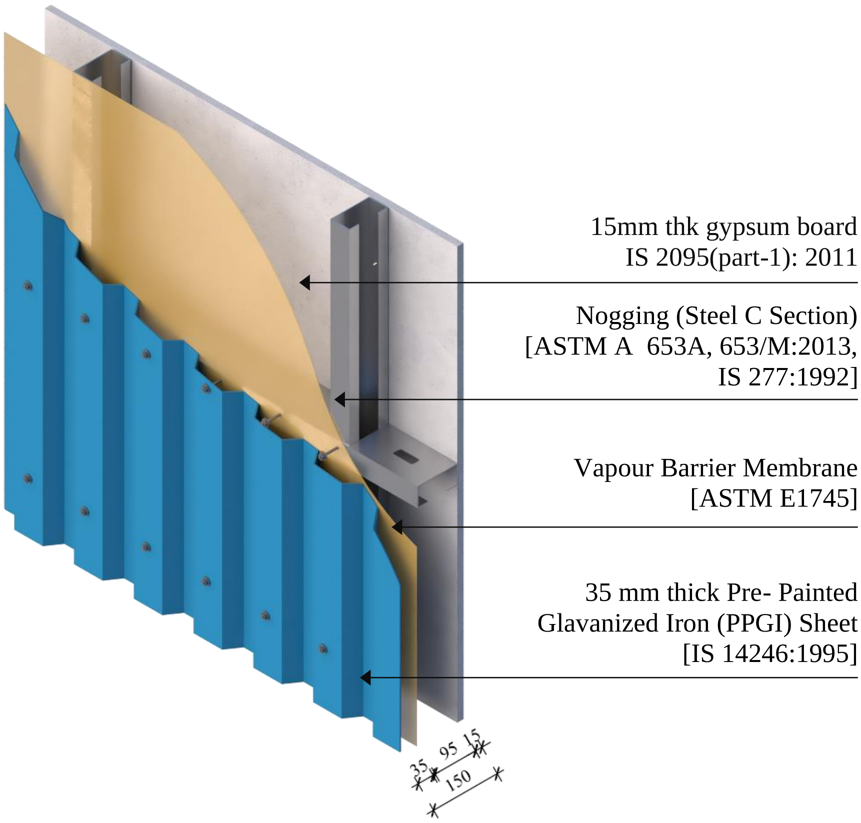


Figure 15: 3D illustration of LGFSS – PPGI sheet with specifications.

Figure 16: Photographs of LGFSS with EPS wall sample (left) & the sample wall installed within the specimen frame of GHB (right).

Figure 17: Photographs of LGFSS with PPGL sheet wall sample (left) & the sample installed within the specimen frame of GHB (right).

3. Reinforced EPS Core Panel System

Reinforced Expanded Polystyrene (EPS) Core Panel System is a manufactured wall panel system constructed as load-bearing walls or filler walls in buildings with RCC framed structure as shown in Figure 18. The panel consists of an EPS core reinforced with an interconnected framework of zinc-coated wire mesh as illustrated in Figure 19. This assembly is finished on-site with a layer of sprayed concrete on both sides termed as *Shotcreting* or *Guniting* as per IS 9012:1978, as seen in Figure 20. The load-bearing reinforced single bearing EPS Core panel used for the construction of external walls was finalized as per the research criteria. Construction drawings were produced as per details mentioned in the Performance Appraisal Certificate (PAC) issued to manufacturers by BMTPC (BMTPC, 2015).

The sample panel was prepared as per established standards by the manufacturer. The sample wall panel of size 980 mm x 980 mm was delivered to CARBSE and directly fixed for testing into the GHB specimen frame as shown in Figure 20. The illustration in plan and elevation is available for reference in Annexure 2.

Figure 18: Photograph of an affordable housing construction employing Reinforced EPS core panels. Source: (BMTPC, 2017)

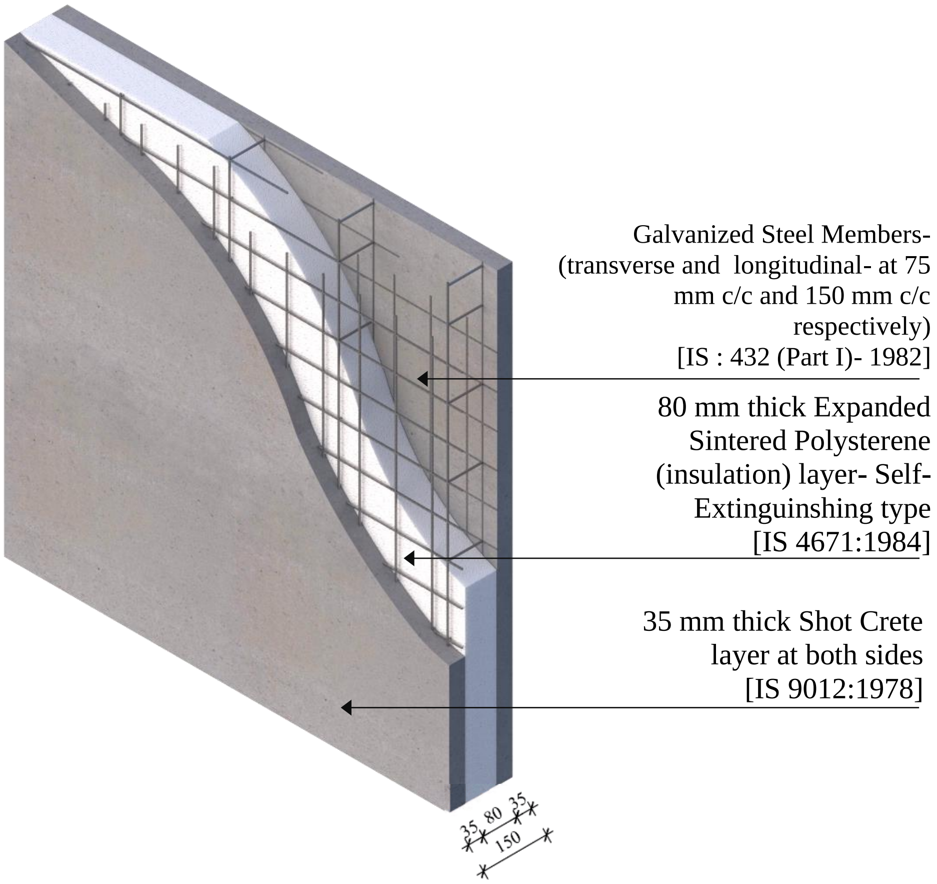


Figure 19: 3d illustration showing specifications of EPS core panel

Figure 20: Example of on-siteshotcreting (left), Sample of EPS core panel received from the manufacturer (middle) and EPS core panel fixed into the specimen frame of GHB (right). Source: (left) (BMTPC, 2018a)

4. Glass Fibre Reinforced Gypsum Panel (GFRG) - Unfilled, partially filled and fully filled

Glass Fibre Reinforced Gypsum (GFRG) Panel is a product made from calcined gypsum, plaster, reinforced with glass fibres and is used for mass housing construction. Details of the same are as per those mentioned in the Performance Appraisal Certificate (PAC) issued to manufacturers by BMTPC (BMTPC, 2011). Class 1 of GFRG panel is mostly used for external wall applications. Each panel is manufactured in 12m length, 3m height and consists of cavities separated by ribs as seen in Figure 23. The panels may be used as unfilled, partially filled or fully-filled, with a concrete and non-structural filling, based on structural applications as shown in Figure 22.

Three samples of GFRG panels were obtained from the manufacturer and were prepared as per standard applications on-site as seen in Figure 24, Figure 25, and Figure 26. The sample of unfilled class 1 water-resistant grade GFRG panel was tested with its hollow cavities and the partially filled panel was tested after the middle cavity was reinforced with an 8mm diameter steel rod and M20 grade concrete. In case of a fully filled panel, middle cavity was filled in the same manner as partially filled panel and all the other cavities were filled with M10 grade concrete (non-structural core filling). Annexure 2 contains illustrations for the same.

Figure 21: Photograph of an affordable housing construction employing GFRG panel. Source: (MoHUA, 2017)

Figure 22: 3D illustrations (top) and photographs of the GFRG Panel samples: Unfilled, partly filled and fully filled (bottom).

Figure 23: Components of a typical GFRG panel (left), on-site preparation of GFRG partly filled panel (middle) and GFRG fully filled panel fixed into the GHB specimen frame (right).

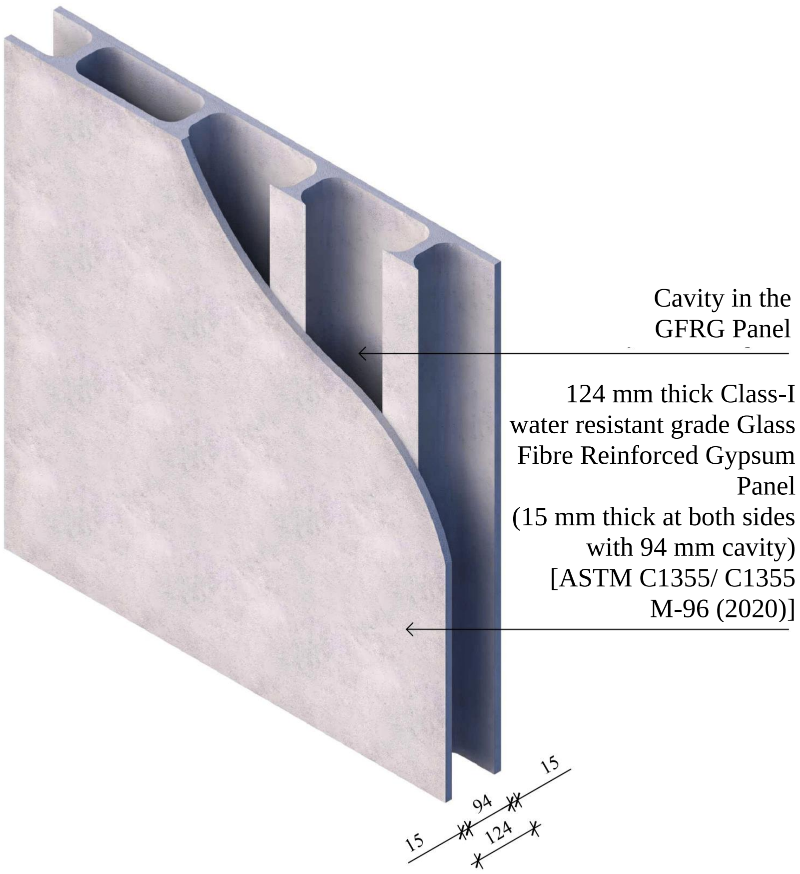


Figure 24: 3d illustration showing specifications of Unfilled GFRG Panel

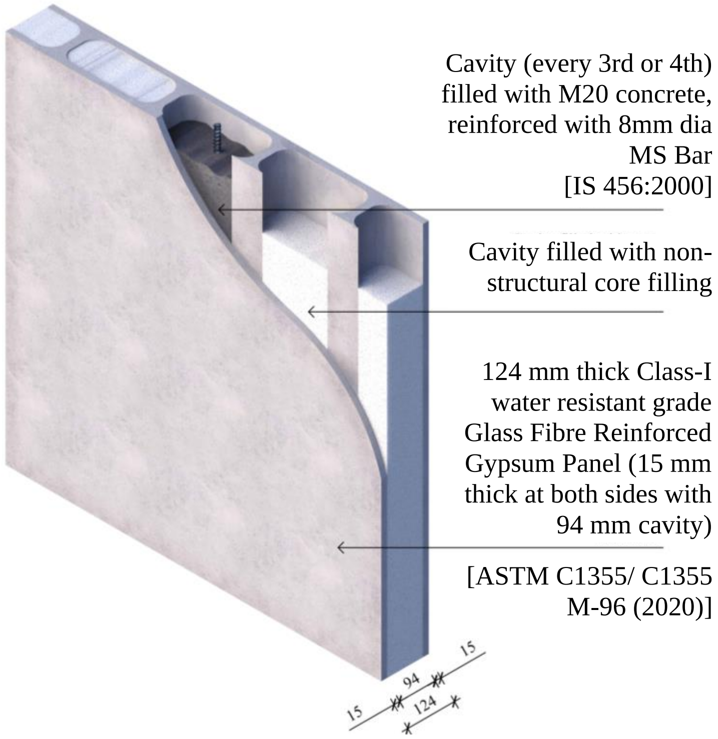


Figure 25: 3d illustration showing specifications of GFRG Panel with RCC and non-structural filling

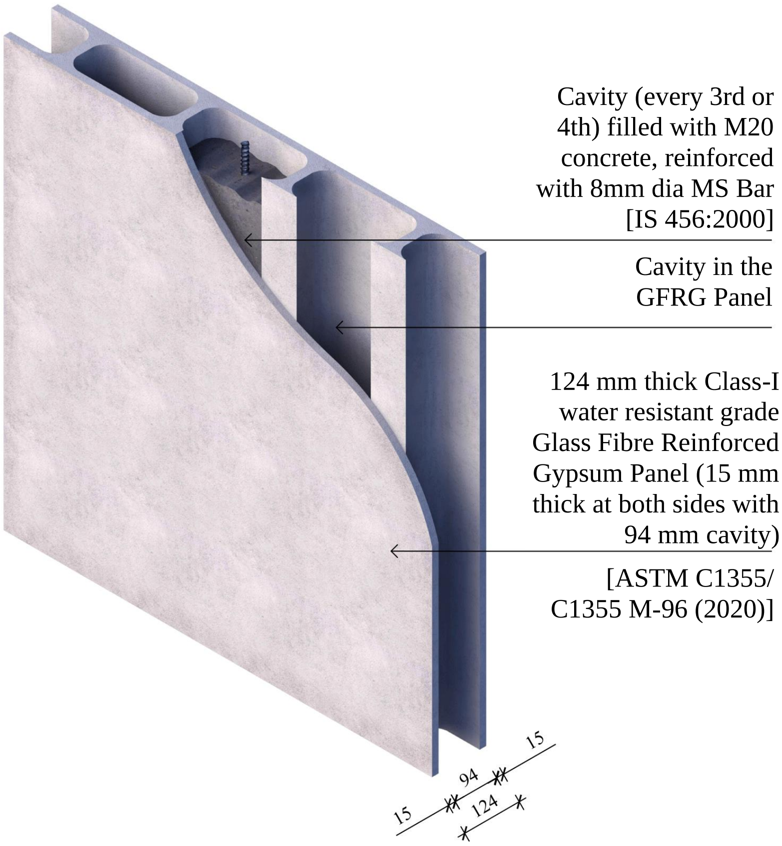


Figure 26: 3d illustration showing specifications of GFRG Panel with partial RCC filling

5. Brick Wall

A conventional brick wall popularly adopted for housing construction in the country, as seen in Figure 27, was also tested as a base case for the purpose of this research. A standard 230 mm thick brick wall with plaster was directly constructed within the specimen frame of GHB using locally available burnt clay bricks from Ahmedabad city, following IS1077 : 1991 for bricks (BIS, 2005) and IS2250 : 1981 for cement mortar (BIS, 1993) as shown in Figure 28. After fully drying and being tested for moisture via thermal imaging, the testing of wall sample was conducted.

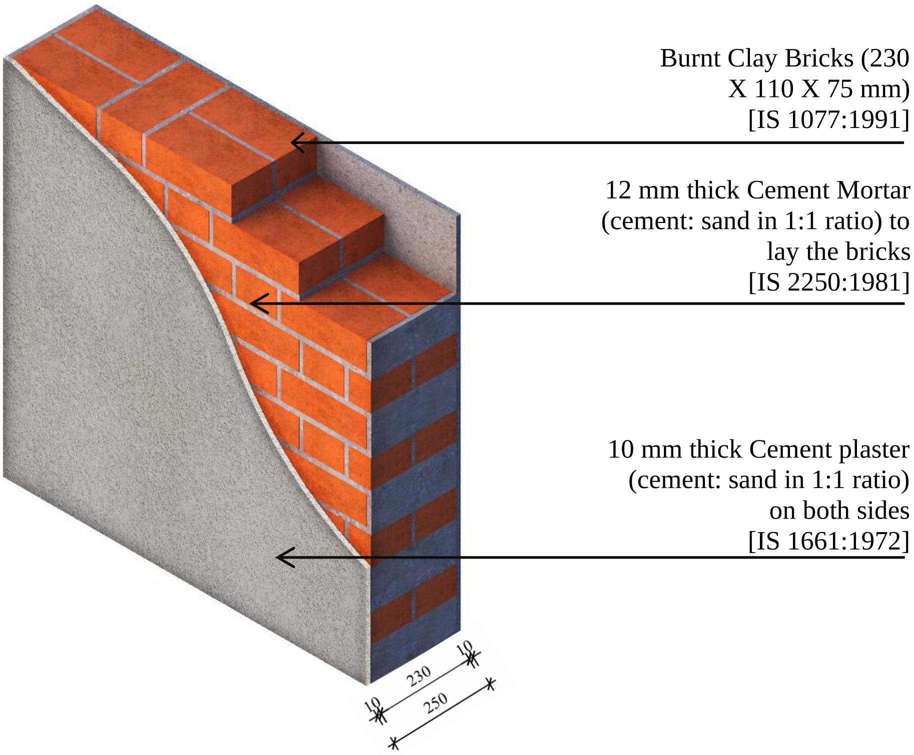


Figure 27: 3D illustration of a conventional brick wall.

Figure 28: Photographs showing brick wall constructed within the specimen frame of GHB.

6. Structural stay-in-place formwork system (Coffor)

Structural stay-in-place formwork system or Coffor technology consists of a structural formwork that is retained as part of the building and concrete is poured in-situ allowing to set along with the formwork, as seen in Figure 29. As illustrated in Figure 30, the formwork consists of two filtering grids made of rib mesh which is reinforced with steel 'C' channels forming vertical stiffeners; the grids on both sides have rebars as horizontal stiffeners and the connectors act as a shear link. The vertical and horizontal stiffeners act as steel reinforcement in the case of a load-bearing wall. Amongst the different types, 'Coffor' insulated panel sample, as seen in Figure 30, was chosen for this research project due to its non-homogeneous nature. Details of the same are as per those mentioned in the Performance Appraisal Certificate (PAC) issued to manufacturers by BMTPC (BMTPC, 2018c).

Since this wall sample assembly of size 980mm x 980mm, that has a concrete core and shotcrete plaster, exceeded the weight that the GHB Box could bear, the sample tested here was trimmed to the size of 460mm x 460mm with no change in its assembly thickness or properties. The remaining area of the specimen frame was covered with 30mm XPS sheets — a high insulating material as seen in Figure 30. Any gaps between the sample and specimen frame were further sealed using XPS insulation strips and finally sealed using silicone sealant. The illustration in plan and elevation is available in Annexure 2.

Figure 29: Photographs of the assembly of 'Coffor' panels without insulation (first) and filled with concrete on-site(second).
Source: (Coffor Construction Company LLD, n.d.)

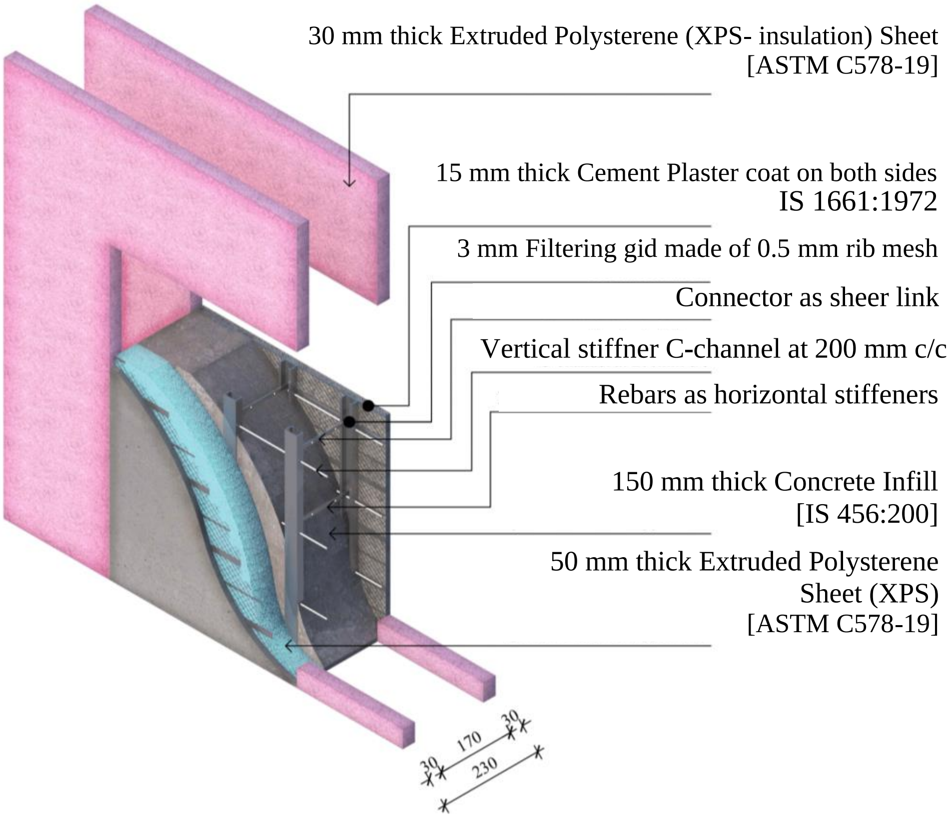


Figure 30: 3D sectional illustration of insulated coffor panel sample used as the specimen for the test.

Figure 31: Photograph of an insulated coffor panel sample without concreting.
Source: (BMTPC, 2018c)

7. Bamboo Crete Wall

In current traditional building practices, this walling method is used as a stronger alternative to Wattle & Daub walling method. Here the concrete plaster substitutes the mud plaster while locally available bamboo remains as the primary reinforcement. Bamboo concrete wall panels can also be used as an infill material in framed structure which gives better ductility and flexibility to the structure. Based on the previous researches it provides assurance that we can use bamboo reinforcement which is most economical and cheaper when compared to conventional steel reinforcement and it is recommended to use in single story building. Considering its credibility, there is a wide scope for designing multi story building using bamboo reinforcement in the future (Rajendran, 2016). Figure 32 shows an illustration of bamboo crete wall.

For the purpose of this research, the bamboo grid and frame were constructed by local craftsmen in the Maroli town, Navsari district, of Gujarat State in India, where this method of construction is still practiced by its tribal population. This wall panel sample was constructed in a perpendicular lattice using untreated hollow split bamboo of 4 to 6 mm thick as seen in Figure 33. For aesthetic outer finish, the convex shape of the split bamboo is faced outside and the concave shape is faced inside the space. The bamboo mesh was attached to a 25mm thick wooden frame of 980mm x 980 mm using iron nails on the edges, to keep the sample sturdy. The bond between bamboo and concrete is much lesser than the bond between steel and concrete. Thus, a sheet of steel chicken wire-mesh of 1/2 inch diameter grid, 22 gauge, 0.7mm thickness, was stretched flat on the aliquant bamboo grid and fixed in place by tying steel wires at several grid intersections. The first layer of 10mm cement plastering 1:6 (Cement to Sand Ratio) was applied on both the sides of the bamboo and steel-mesh assembly by the artisan. As soon as the first layer dried off, the 10mm second layer of the same plaster was applied. This panel required curing for 3-4 days and 3-4 days for drying. This assembly was then transported to the lab and fixed inside the GHB specimen frame as shown in Figure 33. All the edges of the sample were sealed off using silicone. The illustration in plan and elevation is available in Annexure 2.

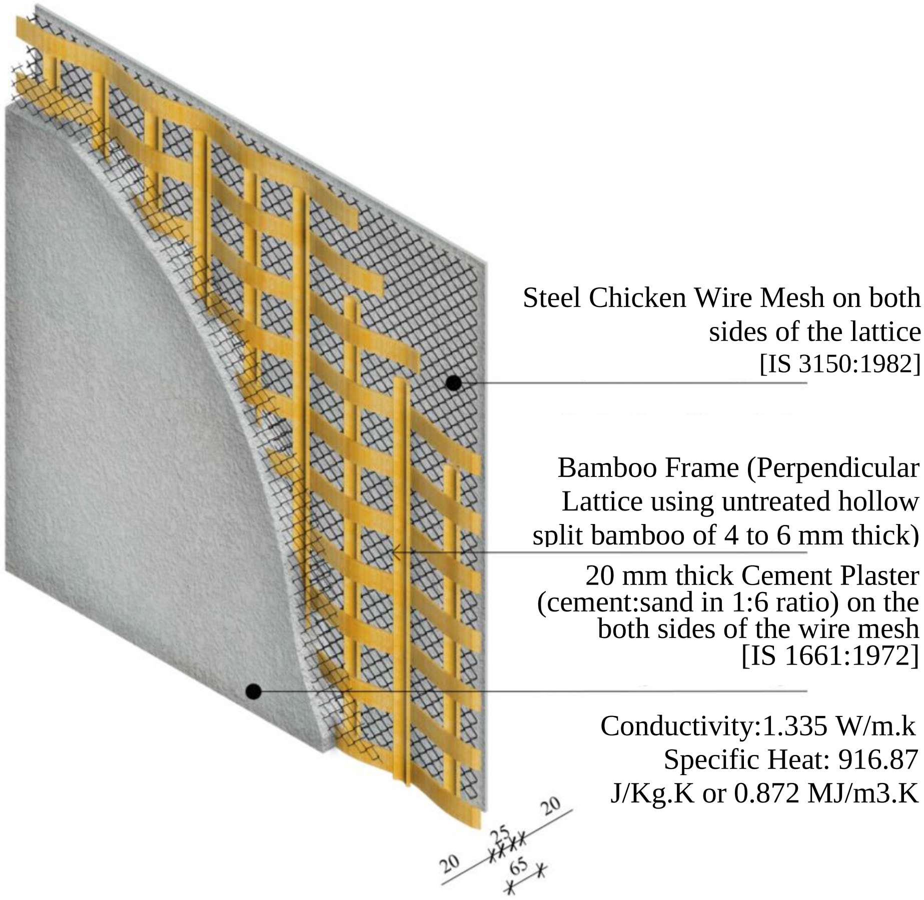


Figure 32: 3d illustration of the bamboo crete wall

Figure 33: Photographs showing the Bamboo crete wall sample without cement plaster constructed regionally by the artisan (left) and Bamboo crete wall sample cement-plastered on both the sides

8. Wattle and Daub Wall

Wattle-and-daub is a walling technology used for making non-load-bearing walls. ‘Wattle’ is made by weaving thin branches or slats between upright stakes. The wattle may be made in place to form the whole of a wall. This sheet is then daubed with ‘Daub’ a combination of wet soil, clay, sand, animal dung and straw. Often, some natural binders, aggregates and reinforcement are added to increase the strength of the wall (Sruthi, 2007). Here, the bamboo acts as a reinforcing material which is good in tension and daub acts as material with good compressive strength due to natural binders used in it. This walling method is being popularly used for panelling in contemporary spatial design as seen in Figure 34. This assembly can be clearly understood from Figure 35.

For the purpose of this research, the wattle and frame were constructed and an estimated quantity of daub was prepared by the local craftsmen of Songadh Taluka, in the Dang district of Gujarat. A 930mm x 930mm wattle was prepared using a couple of 20-25mm wide and only 2-3mm thick untreated bamboo slats by intertwining them alternatively in perpendicular directions as shown in Figure 36. This wattle was then attached to a 980mm x 980mm wooden frame with metal handles for sturdiness. A homogenous daub was separately prepared there using the locally available red soil (64 kgs), cow dung (16 kgs), grass husk (16 kgs) or jute fibres and water (12 litres) in 16:4:4:3 ratio respectively. The red soil is made wet and kept in wet conditions for 3 days. On the 4th day, after pugging the wet red soil using feet, the plaster is finished by mixing the natural stabilizers - cow dung and husk in it using hands. These wattle and daub were transported to the lab to fix the wattle frame in the GHB specimen frame as Figure 37. The daub is made suitable to plaster by the artisan by adding 5-6 litres of water and mixing it well. The first layer of daub, thin enough to cover the exposed bamboo slats was then applied using hands on both the sides of the panel as seen in Figure 36. The first layer is allowed to dry avoiding direct sunlight, the second layer was applied to form a total thickness of 5-6mm on both the sides. After 24 hours of drying time, the third layer of daub of 8-10mm was applied to fill the cavities or cracks developed after drying. The GHB specimen frame was kept exposed to the open environment to dry for 5 days but avoiding direct sunlight as seen in Figure 37. The sample edges were sealed with silicon to avoid the heat transfer through gaps after drying. The illustration in plan and elevation is available in Annexure 2.

Figure 34: Photograph of Wattle-and-Daub technology employed by Hunnarshala Foundation at Khamir Craft Resource Centre, Kutch, Gujarat in the year 2007.
Source: (Matter, n.d.)

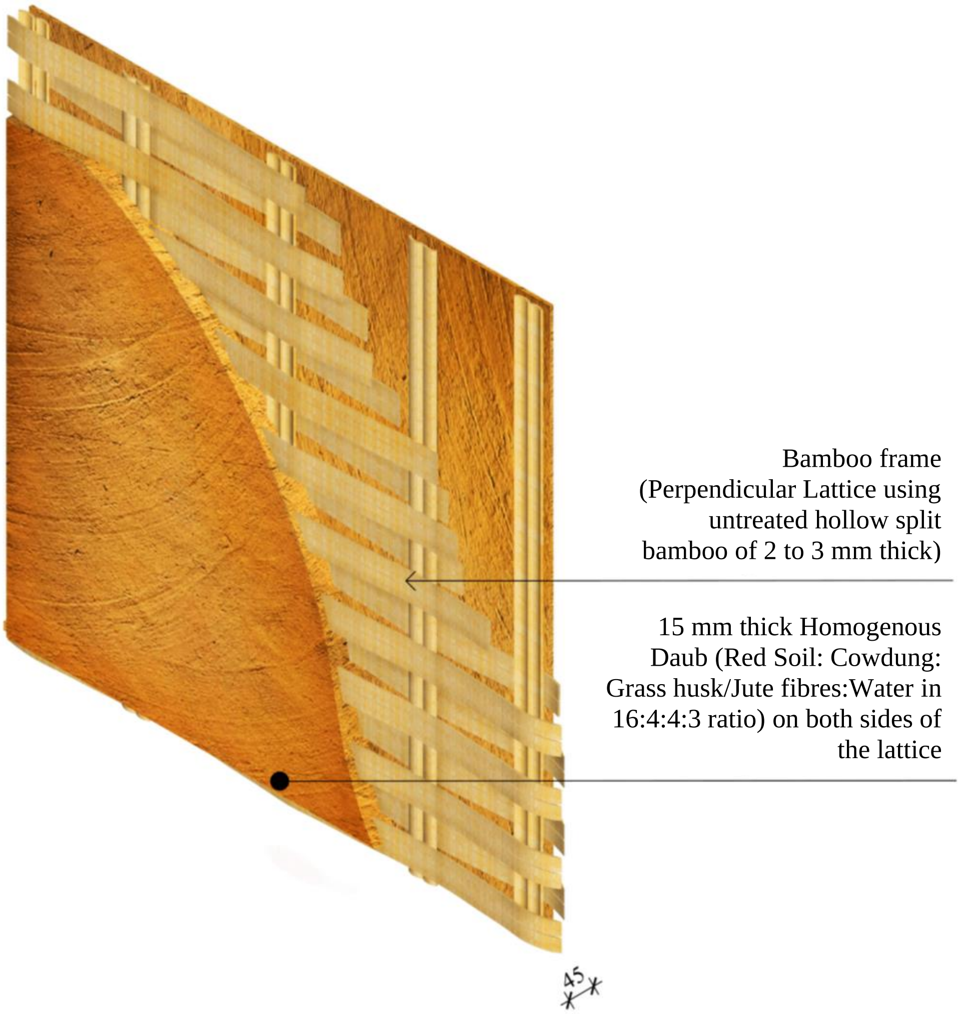


Figure 35: 3d illustration of the wattle-and-daub wall

Figure 36: Photograph showing Wattle prepared by artisans fixed in a wooden frame (left) and Daub prepared regionally and brought to the testing facility for plastering (right).

Figure 37 Application of daub on the wattle (left), GHB specimen frame exposed to outside conditions to dry the walling assembly sample

9. Stabilized Adobe Wall

Adobe or mud brick is one of the oldest building materials in use and abundantly found everywhere with affordable and reasonable cost. In addition to being simple and economic, adobe bricks are fireproof, durable and non-toxic. They possess low sound transmission levels through walls and provide sufficient thermal mass to buildings. Adobe brick walls are load bearing structures, and can be used to build up to several stories high. Also, adobe bricks are suitable to build vaults and domes. They can be simply cut, reshaped and easily subjected to openings. The greatest disadvantage of adobe is its vulnerability to water and rain. (Sahu & Singh, 2017) Studies by (Ngowi, 1997) and (Walker, 1995) have shown that stabilization of earth with suitable stabilizer and reinforcing material either natural or man-made not only improves its durability but also compressive strength. Study by (Sharma et al., 2015) shows that compressive strength of soil increases considerably by addition of fibers. (Sharma et al., 2016) Adobe structures are more common in inhospitable climates and where lumber and other resources are scarce. According to Sustainable Sources, a green building journal, adobe requires less than 1/150th of the energy required to manufacture a similar amount of Portland cement, and less than five times the energy required to produce ordinary brick. (Gromicko, n.d.). This assembly can be referred from Figure 38.

For the purpose of this research, around 75 stabilized adobe blocks of 230 x 230 x 75 mm each and the mud mortar mix were prepared by the local artisans in the North Gujarat region. For the stabilized adobe blocks, a dry mix composed of soil, sand and cement was first prepared. Then water was added to this mix, and pugging was done to attain a wet mixture. Later, husk was added as reinforcement to mixture while pugging and adding water, as a binder material. The ratio of soil, sand, cement and husk being 9:3:1/2:4.5. The mixture was then poured in a wooden formwork, and kept for 15-20 mins. The blocks were removed from the formwork and kept in a shaded place to dry. These blocks were cured for 10-15 days by sprinkling water on them rather than directly spraying on top of them. Mud mortar is a mixture of clayey soil and sand which is used as a binder to hold the blocks. The ratio for the mud mortar used in the sample was 1 sand: 5 soil. These materials were then transported to the lab to construct the masonry directly into the GHB specimen frame. The cutting of blocks was done on site as per GHB specimen frame size. The blocks are laid on the wet mortar to align and set easily to allow some movement while construction of the wall as seen in Figure 39. After allowing the finished wall to dry for 36 hours, the sample edges were sealed with silicon to avoid the heat transfer through gaps. The illustration in plan and elevation is available in Annexure 2.

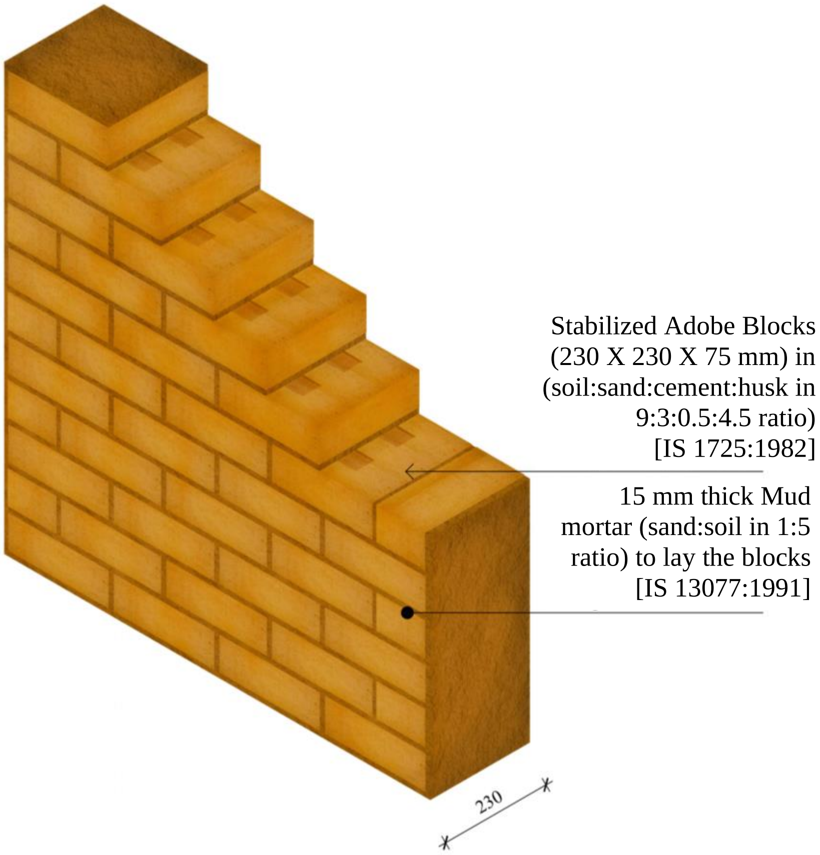


Figure 38: 3d illustration showing specifications of the stabilized adobe wall

Figure 39: Photographs of (a)Pugging of the mud mix for the adobe; (b) Pouring mud mix in the mould; (c)Removing blocks from the mould; (d) Levelling of a course of the blocks; (e) Dried stabilized adobe wall

10. Laterite Block Wall

Laterite is well known in Asian countries as a building material for more than 1000 years. (Schellmann, n.d.) Lateritic soils can be found in two natural states: Soft soils, which harden when exposed to air due to chemical reaction. Such soils can be found on the west coast of India, from Kerala to Goa; Hard crust which used to be a soil and has already hardened. Orissa in India show wonderful examples of such soils and blocks. (Auroville Earth Institute, n.d.)

The laterite clay is diffused in immense masses, without any appearance of stratification and is placed over the granite that forms the basis of Malayala. It is full of cavities and pores, and contains a very large quantity of iron in the form of yellow and red ochres. In the mass, while excluded from the air, it is dug up in square masses with a pick-axe, and immediately cut into desired shape with a trowel. Soon after, it becomes hard as brick, and resists the air and water much better than other clay bricks in India. (Schellmann, n.d.) It is estimated that 2.83cum(100 cu-ft) of soil is excavated in each load. (Nasheed et al., n.d.) The blocks shall be exposed preferably for a period of three months before being used in the construction of masonry to ensure adequate stabilization. The standard laterite block sizes available in India are 390 x 190 x 190mm, 490 x 190 x 190mm and 590 x 290 x 290mm. (BIS, 2003) Most common weathering damages namely granular disintegration, bio-degradation and salt attack stem from presence of moisture. Hence protection from dampness prolongs the life of laterite masonry. (Kasthurba et al., 2006) Figure 41 shows a 3D illustration of the laterite block wall.

For the purpose of this research, laterite blocks of 355 x 205 x 92mm size were sourced from Ratnagiri district of Maharashtra in India. Using locally sourced sand and soil from Ahmedabad city, mud mortar of 1 sand: 5 soil ratio was used as a binder to hold the blocks. This masonry was directly constructed in the GHB specimen frame requiring cutting of the blocks in-situ as seen in Figure 40. The finished wall was left to dry for 48 hours before thermal imaging and testing as seen in Figure 42.

Figure 40: Photograph of the artisan cutting the laterite block to fit each course into the specimen frame; Sideways photograph of the reduced laterite block (right)

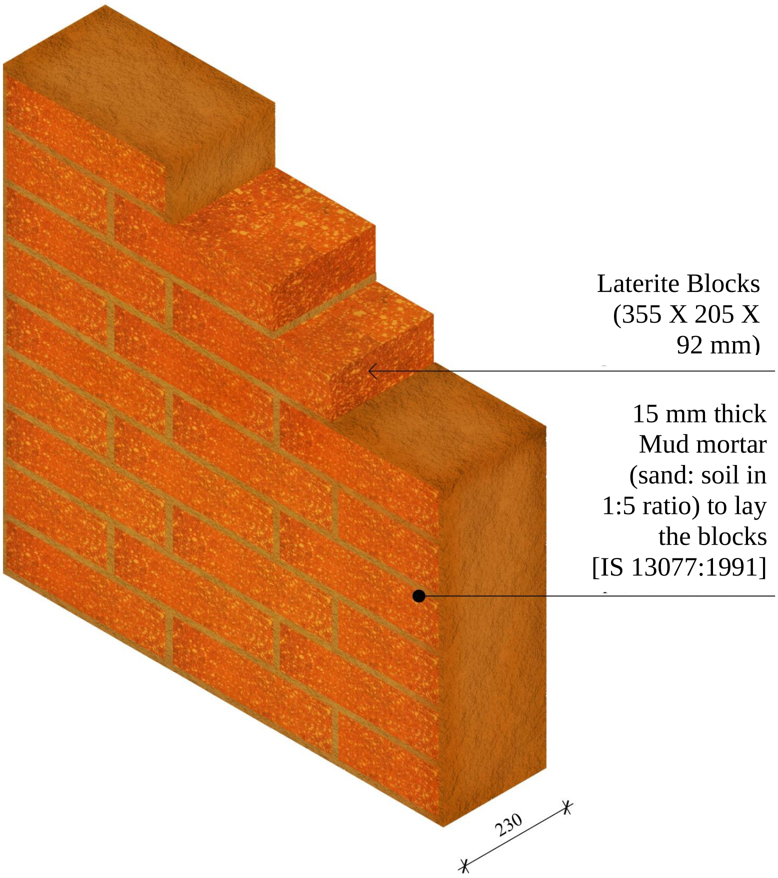


Figure 41: 3d illustration of the laterite block wall

Figure 42 Left-Right: Photograph of the artisan cutting the laterite block to fit each course into the specimen frame; Sideways photograph of the reduced laterite block (right)

11. Unstabilized Adobe Wall

Adobes are made of thick malleable mud, often added with straw. After being cast, they are left to dry under sun. They are traditionally either hand shaped or shaped in parallelepiped wooden moulds. The name adobe comes from the Egyptian hieroglyph, meaning brick. It has passed via Coptic in Arabic, as Al-ţŭb. When Arabs invaded Spain and France, the word has been deformed progressively as a *Thob*, a *Dob* and it became finally adobe in French and in English. (Auroville, n.d.)

For the purpose of this research, around 75 unstabilized adobe blocks of 230 x 230 x 75 mm each and the mud mortar mix were prepared by the local artisans in the North Gujarat region. For the unstabilized adobe blocks, a dry mix composed of husk, sand and soil in 4.5:3:9 ratio was first prepared. Then water was added to this mix, and pugging was done to attain a wet mixture. Later, husk was added as reinforcement to mixture while pugging and adding water, as a binder material. The ratio of soil, sand, cement and husk was 9: 3: 0.5: 4.5. The mixture was then poured in a wooden formwork, and kept for 15-20 mins. The blocks were removed from the formwork and kept in a shaded place to dry for at least 15-20 days. No curing was required due to absence of stabilizers. The ratio for the mud mortar used in the sample was 1 sand: 5 soil. These materials were then transported to the lab to construct the masonry directly into the GHB specimen frame. The assembly can be referred from Figure 43. The cutting of blocks was done on site as per GHB specimen frame size. The blocks were laid on the wet mortar to align and set easily to allow some movement while construction of the wall as seen in Figure 44. The wall was left to dry for 36 hours. The illustration in plan and elevation is available in Annexure 2.

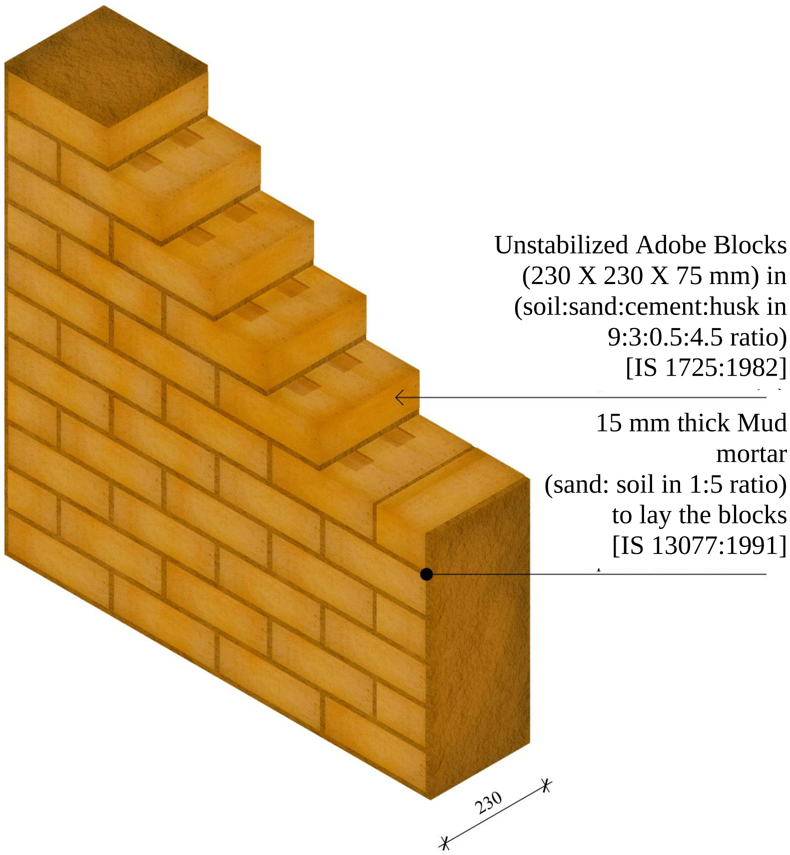


Figure 43 3d illustration of the unstabilized adobe wall

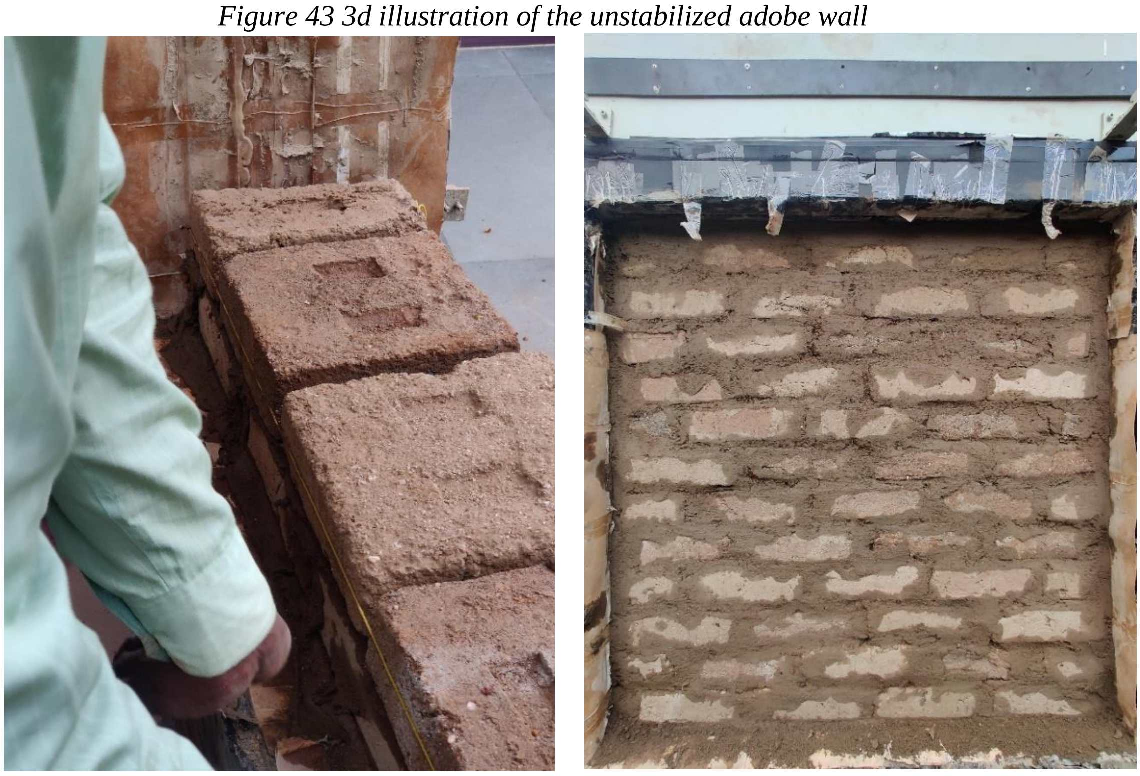


Figure 44 Artisan laying the second course of the unstabilized adobe (left); Completed wall assembly of the unstabilized adobe (right)

12. Compressed Stabilized Earth Block (CSEB) Wall

Compressed Stabilised Earth Blocks (CSEBs) are non-fired blocks with a mix of soil, sand, water and 5% cement as a stabilizer. They are compressed in a motorised or a manual press and cured for 28 days. (Maïni, n.d.) Some of the advantages of using CSEBs for construction are that they can be made on site and their manufacture needs much less energy and reduces pollution (a CSEB uses 10.7 times less energy to make than a country fired brick). (AVEI, n.d.) Refer this wall assembly from Figure 45.

For the purpose of this research, around 75 stabilized adobe blocks of 230 x 230 x 75 mm each and the mud mortar mix were prepared by the local artisans in the North Gujarat region. For the unstabilized adobe blocks, a dry mix composed of husk, sand and soil in 4.5:3:9 ratio was first prepared. Then water was added to this mix, and pugging was done to attain a wet mixture. Later, husk was added as reinforcement to mixture while pugging and adding water, as a binder material. The ratio of soil, sand, cement and husk being 9:3:1/2:4.5. The mixture was then poured in a wooden formwork, and kept for 15-20 mins. The blocks were removed from the formwork and kept in a shaded place to dry for at least 15-20 days. No curing was required as no stabilizers were added to the composition. The ratio for the mud mortar used in the sample was 1 sand: 5 soil. These materials were then transported to the lab to construct the masonry directly into the GHB specimen frame. The cutting of blocks was done on site as per GHB specimen frame size. The blocks are laid on the wet mortar to align and set easily to allow some movement while construction of the wall. The process can be seen in Figure 46. After allowing the finished wall to dry for 36 hours, the sample edges were sealed with silicon to avoid the heat transfer through gaps. The illustration in plan and elevation is available in Annexure 2.

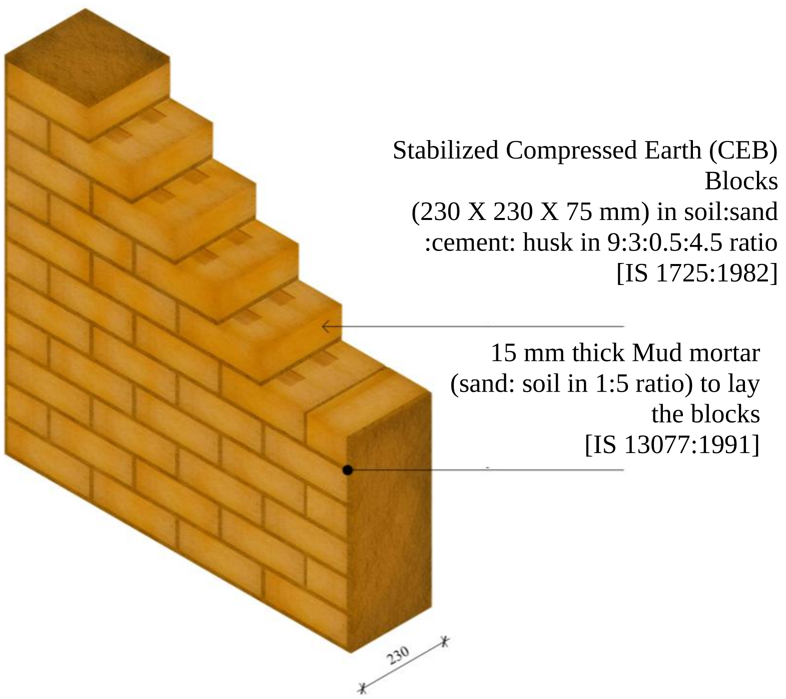


Figure 45 3d illustration of the CSEB wall

Figure 46 (a) Making of the CSEB mix; (b) Filling the mix in the mould of the press machine; (c) Compressing the mix using a manual press machine; (d) Preparation of the mortar for assembly; (e) Laying of the second course of the CSEB; (d)Finishing of the CSEB wall assembly in the GHB box.

13. Unstabilized Compressed Earth Block (CEB) Wall

The most common stabilizers used for CSEB production are cement and lime. Lime is more environment friendly than cement. Lime-stabilized blocks can be used for single-story buildings, while the combination of lime and cement stabilizers helped to obtain higher compressive strengths than that of lime alone. (Malkanthi et al., 2020) Refer this wall assembly from Figure 47.

For the purpose of this research, around 55 unstabilized compressed-earth-blocks of 230 x 230 x 105 mm each and the mud mortar mix were prepared by the local artisans in the North Gujarat region. For the unstabilised CEB, first the dry mixture is prepared with sand soil in 1:3 ratio and mixed properly. Lime water is added to the mixture, in such a way that it's not too much wet or dry. Lime water acts as a stabilizer here. Wet enough to form a lump and dry enough to break when dropped from a height. The mixture is then poured in a metal mould fixed in the block-compress-machine, properly filled till the top and compressed to form the blocks. The blocks are removed from the mould and kept in a shaded place. These blocks are cured for 10-15 days by sprinkling water on them rather than directly spraying on top of them. The blocks are kept to dry in a shaded area for at least 15-20 days. The unstabilized CEB blocks were covered with a wet jute cloth for 10 days before the sample assembly. This was done to avoid the formation of cracks because of the reaction from the lime water. This chemical reaction can also form a new material such as a pozzolana. After that it is kept to dry in a shaded area before using it for the sample wall. The ratio for the mud mortar used in the sample was 1 sand: 5 soil.

These materials were then transported to the lab to construct the masonry directly into the GHB specimen frame. The cutting of blocks was done on site as per GHB specimen frame size. This can be seen in Figure 48. The blocks are laid on the wet mortar to align and set easily to allow some movement while construction of the wall. After allowing the finished wall to dry for 36 hours, the sample edges were sealed with silicon to avoid the heat transfer through gaps. The illustration in plan and elevation is available in Annexure 2.

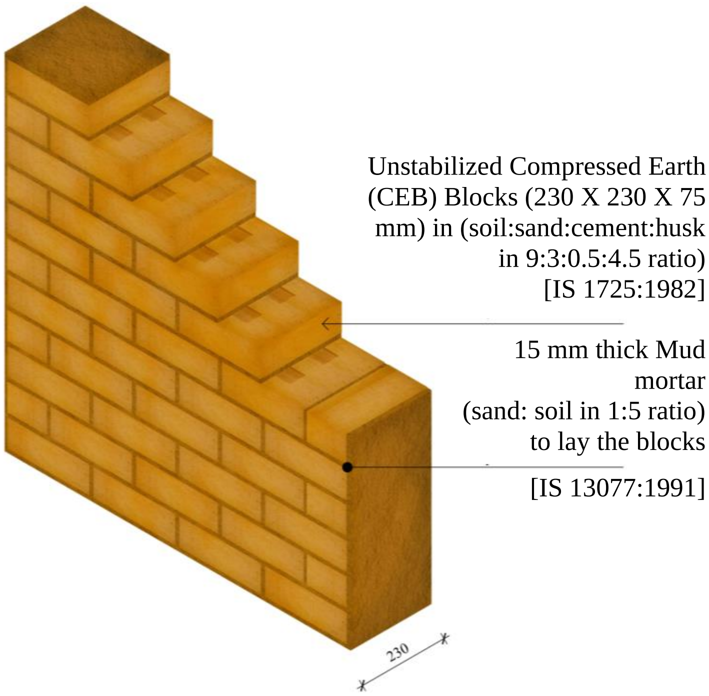


Figure 47 3d illustration of unstabilized compressed earth block wall

Figure 48 Cutting the unstabilized CEB for the second course unit (left); Finished unstabilized CEB wall assembly in the GHB box.

14. Autoclaved Aerated Concrete (AAC) Block Wall with Perlite-based cement plaster

Autoclaved aerated concrete (AAC) is a lightweight, precast, thermally insulating building material used to produce concrete masonry unit (CMU) like blocks for building construction. AAC is manufactured from fly ash, lime, gypsum, aluminium, cement, sand, and other raw materials. AAC blocks are advantageous because they simultaneously provide structure, insulation, and fire- and mold-resistance while being easy to construct with. Moreover, due to the bigger size of individual blocks, they require less mortar than a clay brick wall of same size. Refer this walling technology in Figure 49.

In current traditional building practices, the AAC block wall is constructed, typically with regular cement mortar and finished with plaster. For the purpose of the research, this walling technology was constructed using Perlite-based cement as the plaster for finishing and regular cement mortar between the AAC blocks. This type of plaster is thermally insulating and inhibits heat transfer from either side. Both AAC blocks and perlite-based cement plater were procured from Ahmedabad, Gujarat. The readily available AAC blocks of standard size in India, 600mm x 200mm x 100mm or 24” x 8” x 4” were used. A 5mm thk layer of cement mortar was applied between AAC block. The plaster applied to both sides of the wall was 20mm thick. The illustration in plan and elevation is available in Annexure 2.

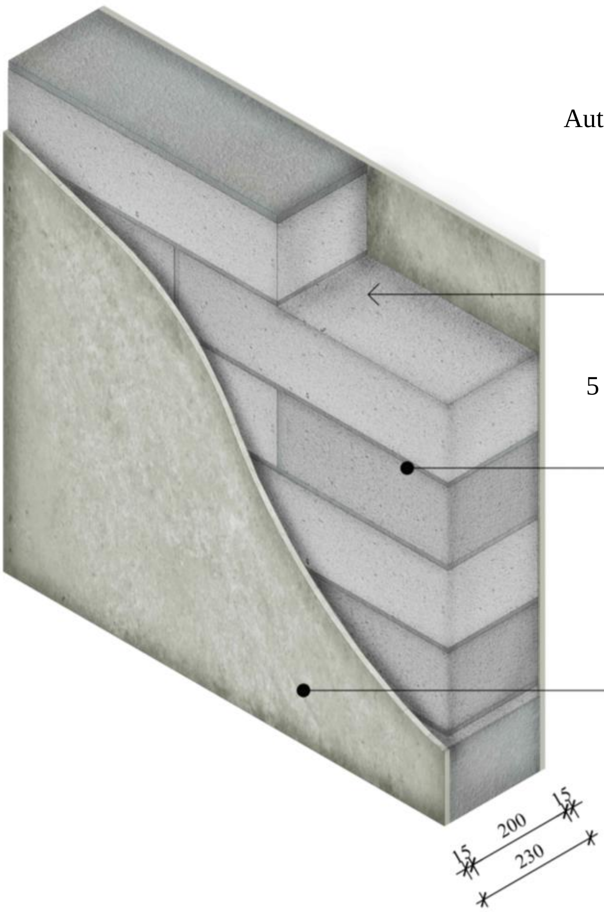


Figure 49: 3d illustration of AAC block wall

15. Unstabilized Rammed Earth Wall

Rammed earth wall is one of the oldest construction techniques. It involves compacting layers of soil in a formwork. Upon drying, it results in a dense monolithic wall. The best suited soils for rammed earth construction are sandy or gravely soils. In case, the nautral soil is too dry, it is moistened and thoroughly mixed to obtain a uniformly humid mix. This technique relies on the self-weight of the wall to hold it in place. Also, rammed earth walls have high thermal mass.

First, dry mixture was prepared with sand, soil, and aggregate in the 2:6:4 ratio. Next, lime water was sprinkled on the mixture to prevent excessive wetting. The prepared mixture was wet enough to form lumps in hand but dry enough to allow breakage when dropped from a height. This mixture was poured into a wooden formwork up to a height of around 10 cm and then rammed. The process was repeated to form consistent layers. A geo-grid wire mesh was used between the layers for reinforcement. After compression, the density was checked using a penetrometer. After completion, the formwork was carefully dismantled to avoid cracking on edges.

The materials were transported to the lab and then installed in the GHB specimen as seen in Figure 51. The whole wall was divided into 4 parts for the ease of logistics. The blocks were chiseled for accommodation within the sample holder. Next, cement mortar was applied to fix the blocks on the sample holder frame. The blocks were then laid on the wet mud mortar to align and set easily by allowing some movement during the construction. The sand to soil ratio used to prepare the mud mortar applied between the blocks was 1:5. The finished wall was left to dry for 24-36 hours before thermal imaging and testing began. The illustration in plan and elevation is available in Annexure 2.

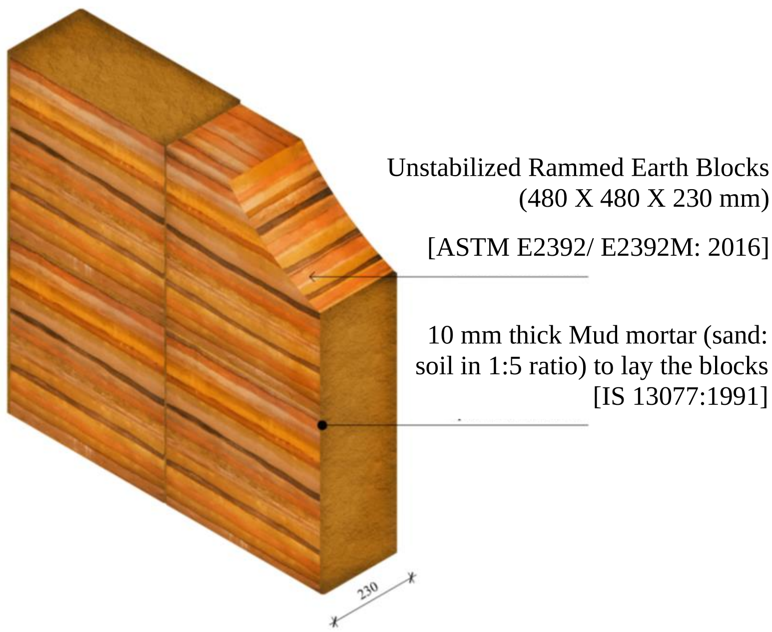


Figure 50: 3D illustration of Unstabilized rammed earth wall.

Figure 51: Unstabilized rammed earth block and wall sample preparation.

16. Stabilized Rammed Earth Wall

To obtain higher load bearing capacities, stabilizer can be added to the soil before the ramming stage. When added in appropriate amount, cement acts as a good stabilizing agent.

First, dry mixture was prepared with cement, sand, soil, and aggregate in the 1:2:6:4 ratio. Next, lime water was sprinkled on the mixture to prevent excessive wetting. The prepared mixture was wet enough to form lumps in hand but dry enough to allow breakage when dropped from a height. This mixture was poured into a wooden formwork up to a height of around 10 cm and then rammed. The process was repeated to form consistent layers. A geo-grid wire mesh was used between the layers for reinforcement. After compression, the density was checked using a penetrometer. After completion, the formwork was carefully dismantled to avoid cracking on edges.

The materials were transported to the lab and then installed in the GHB specimen. The whole wall was divided into 4 parts for the ease of logistics. The blocks were chiseled for accommodation within the size of GHB sample holder. Next, cement mortar was applied to fix the blocks on the sample holder frame. The blocks were then laid on the wet mud mortar to align and set easily by allowing some movement during the construction. The sand to soil ratio used to prepare the mud mortar applied between the blocks was 1:5. The finished wall was left to dry for 24-36 hours before thermal imaging and testing began. The illustration in plan and elevation is available in Annexure 2.

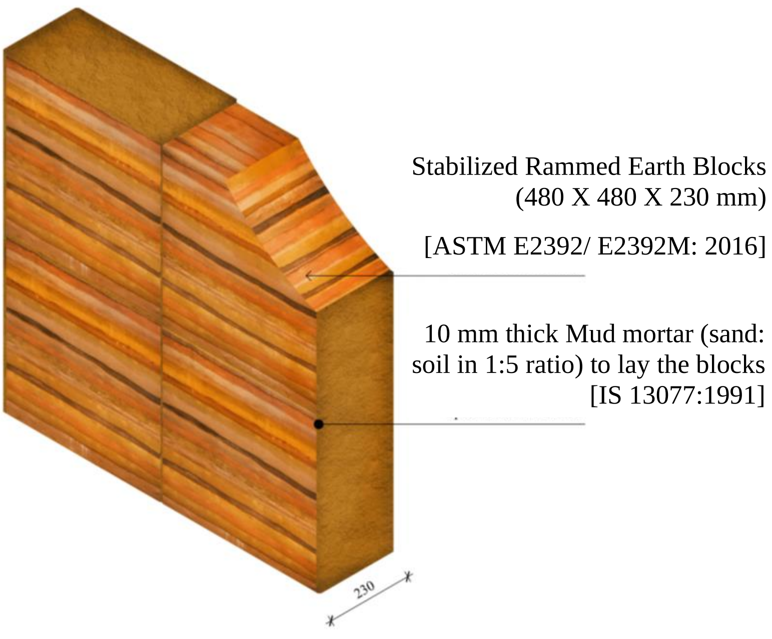


Figure 52: 3D illustration of Stabilized rammed earth wall

Figure 53: Stabilized rammed earth block and wall sample preparation.

17. AAC Block Wall with Cement Mortar and Cement Plaster

Autoclaved aerated concrete (AAC) is a lightweight, precast, thermally insulating building material used to produce concrete masonry unit (CMU) like blocks for building construction. AAC is manufactured from fly ash, lime, gypsum, aluminium, cement, sand, and other raw materials. AAC blocks are advantageous because they simultaneously provide structure, insulation, and fire- and mold-resistance while being easy to construct with. Moreover, due to the bigger size of individual blocks, they require less mortar than a clay brick wall of same size. Refer this walling technology in Figure 54.

The materials were transported to the lab and the wall was constructed in the GHB specimen. Cement mortar was applied to fix the blocks on the sample holder frame. The blocks were then laid on the wet mortar to align and set easily by allowing some movement during the construction. The cement to sand ratio used to prepare the cement mortar applied between the blocks was 1:4. The wall was left for 24 hours for the mortar to dry. Next, the cement plaster was prepared in mentioned ratio and applied to finish the wall surface. The completed sample was left to dry for 10 days before thermal imaging and testing began. The illustration in plan and elevation is available in Annexure 2.

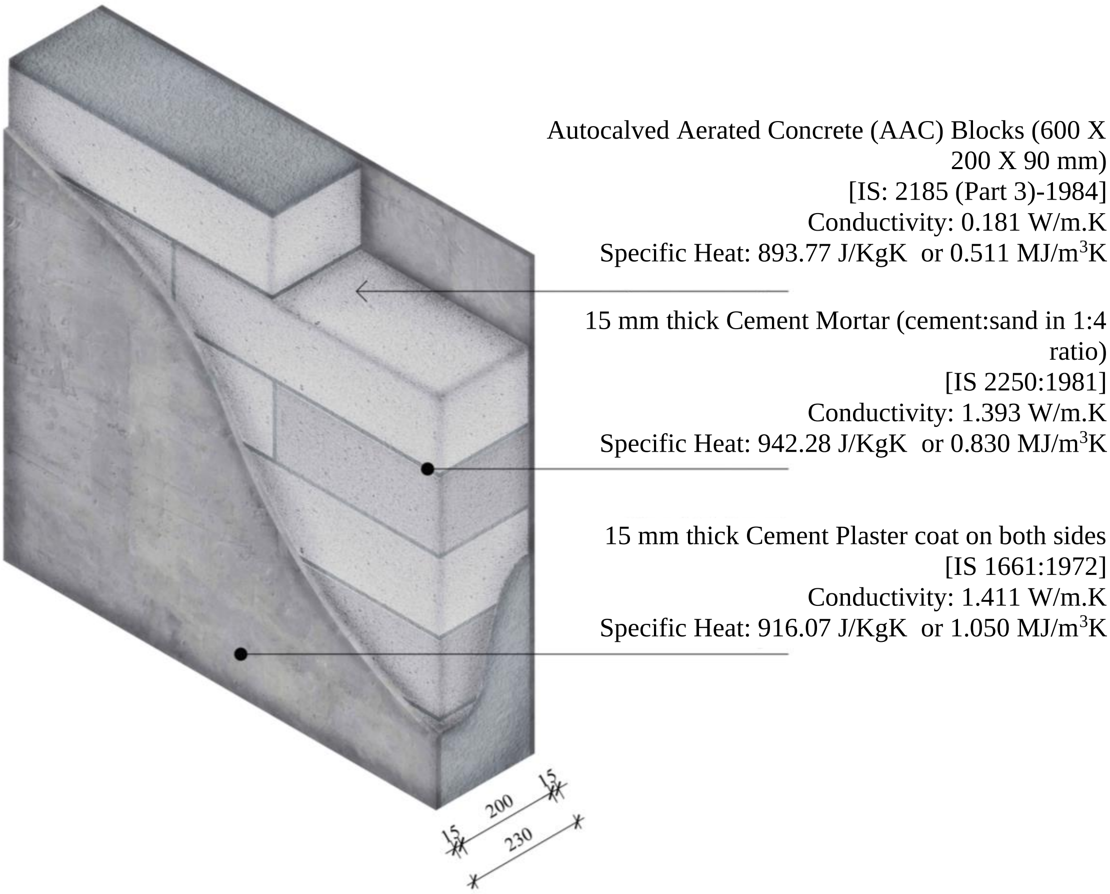


Figure 54: 3D Illustration of AAC block wall with cement mortar and cement plaster

18. AAC Block Wall with Lime Mortar and Lime Plaster

Industrially manufactured, precast AAC blocks can be used to construct insulating walls with suitable block-bedding and wall finishing materials. Apart from cement, lime mortar and lime plaster are suitable materials in AAC block wall construction. Lime mortar used for above ground construction is called non-hydraulic lime. Refer this walling technology in Figure 55.

In order to prepare lime mortar, quicklime was first slaked or hydrated for 3-4 days. Next, it was mixed with sieved sand in the ratio 1:3. Similarly, lime plaster was prepared by combining lime and sand in the ratio 1:4 after hydration of quick lime was complete.

The materials were transported to the lab and the wall was constructed in the GHB specimen as seen in Figure 56. The wall was directly constructed in the sample holder. Lime mortar was applied to fix the blocks on the sample holder frame. The blocks were then laid on the lime mortar to align and set easily by allowing some movement during the construction. The sample was left for a day for the mortar to dry. Lime plaster was applied on the next day for wall finishing. The completed wall was left to dry for 5-6 days before thermal imaging and testing began. The illustration in plan and elevation is available in Annexure 2.

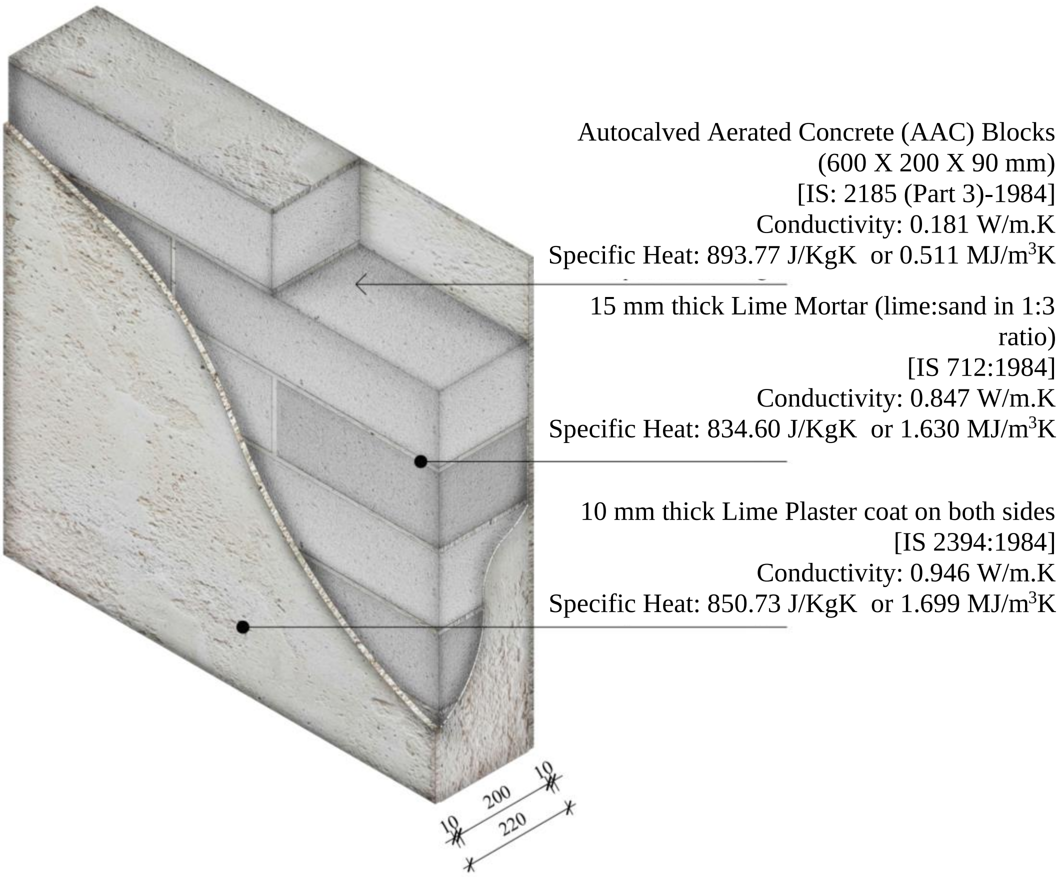


Figure 55: 3D Illustration of AAC block wall with lime mortar and lime plaster

Figure 56: Preparation of AAC block wall with lime mortar and lime plaster.

19. Burnt Clay Brick Wall with Lime Mortar and Lime Plaster

Burnt clay brick is one of the most common materials used in wall construction. Due to faster setting time, brick walls are typically constructed with cement mortar. However, lime mortar is also commonly used as an alternative to cement mortar. When quick lime is thoroughly mixed with enough water, it forms a slurry which is used as mortar. This non-hydraulic lime slurry naturally turns back to calcium carbonate by reacting with carbon dioxide in the air. This process is called the lime cycle.

In order to prepare lime mortar, quicklime was first slaked or hydrated for 3-4 days. Next, it was mixed with sieved sand in the ratio 1:3. Similarly, lime plaster was prepared by combining lime and sand in the ratio 1:4 after hydration of quick lime was complete.

The materials were transported to the lab and then installed in the GHB specimen as seen in Figure 58. The wall was directly constructed in the sample holder. Lime mortar was applied to fix the blocks on the sample holder frame. The blocks were then laid on the lime mortar to align and set easily by allowing some movement during the construction. The sample was left for a day for the mortar to dry. Lime plaster was applied on the next day for wall finishing. The completed wall was left to dry for 5-6 days before thermal imaging and testing began. The illustration in plan and elevation is available in Annexure 2.

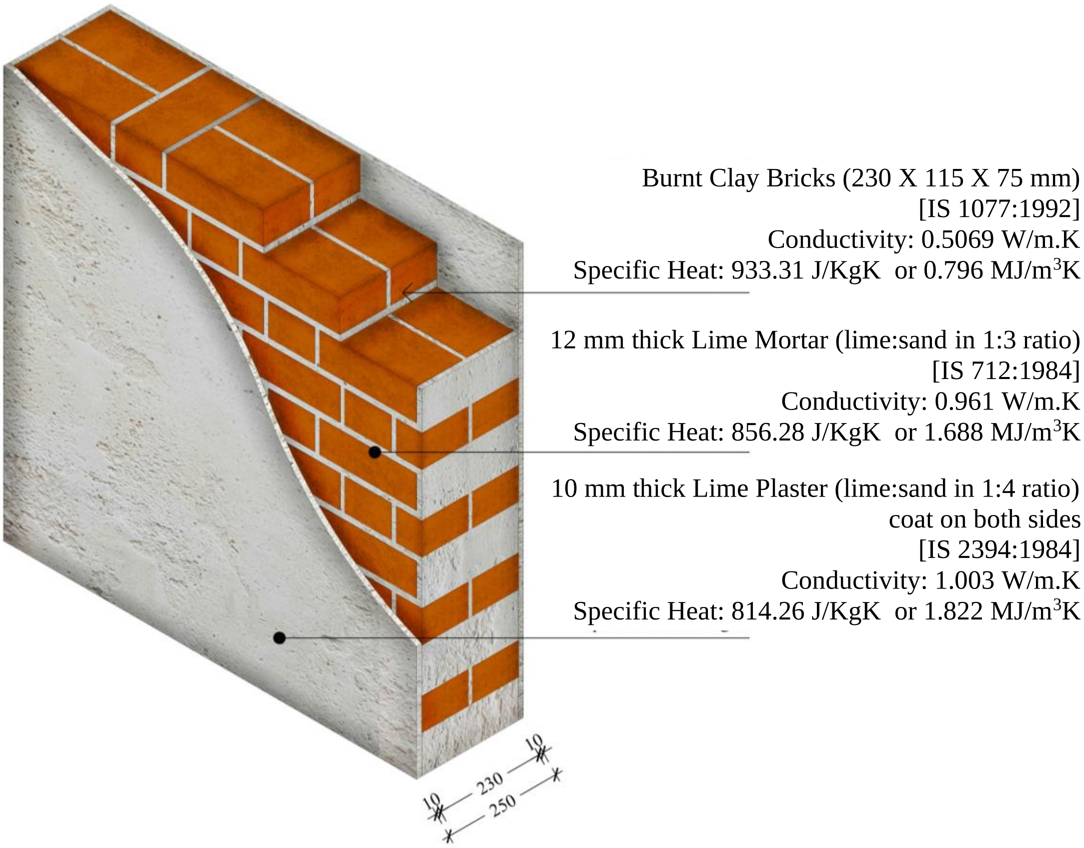


Figure 57: 3D Illustration of burnt clay brick wall with lime mortar and lime plaster

Figure 58: Preparation of burnt clay brick wall with lime mortar and lime plaster.

20. Limestone Wall with Lime Mortar and Lime Plaster

Limestone is a common carbonate sedimentary rock, used in construction for centuries. Metamorphosis of limestone results in marble. Limestone is long-lasting due to higher resistance to weathering. It is easy to cut into block form for more elaborate carving.

For the purpose of this research limestone blocks of size 355 mm x 200mm x 140mm were sourced from Junagadh. In order to prepare lime mortar, quicklime was first slaked or hydrated for 3-4 days. Next, it was mixed with sieved sand in the ratio 1:3. Similarly, lime plaster was prepared by combining lime and sand in the ratio 1:4 after hydration of quick lime was complete.

The materials were transported to the lab and then installed in the GHB specimen as seen in Figure 60. The wall was directly constructed in the sample holder. Lime mortar was applied to fix the blocks on the sample holder frame. The blocks were then laid on the lime mortar to align and set easily by allowing some movement during the construction. The sample was left for a day for the mortar to dry. Lime plaster was applied on the next day for wall finishing. The completed wall was left to dry for 5-6 days before thermal imaging and testing began. The illustration in plan and elevation is available in Annexure 2.

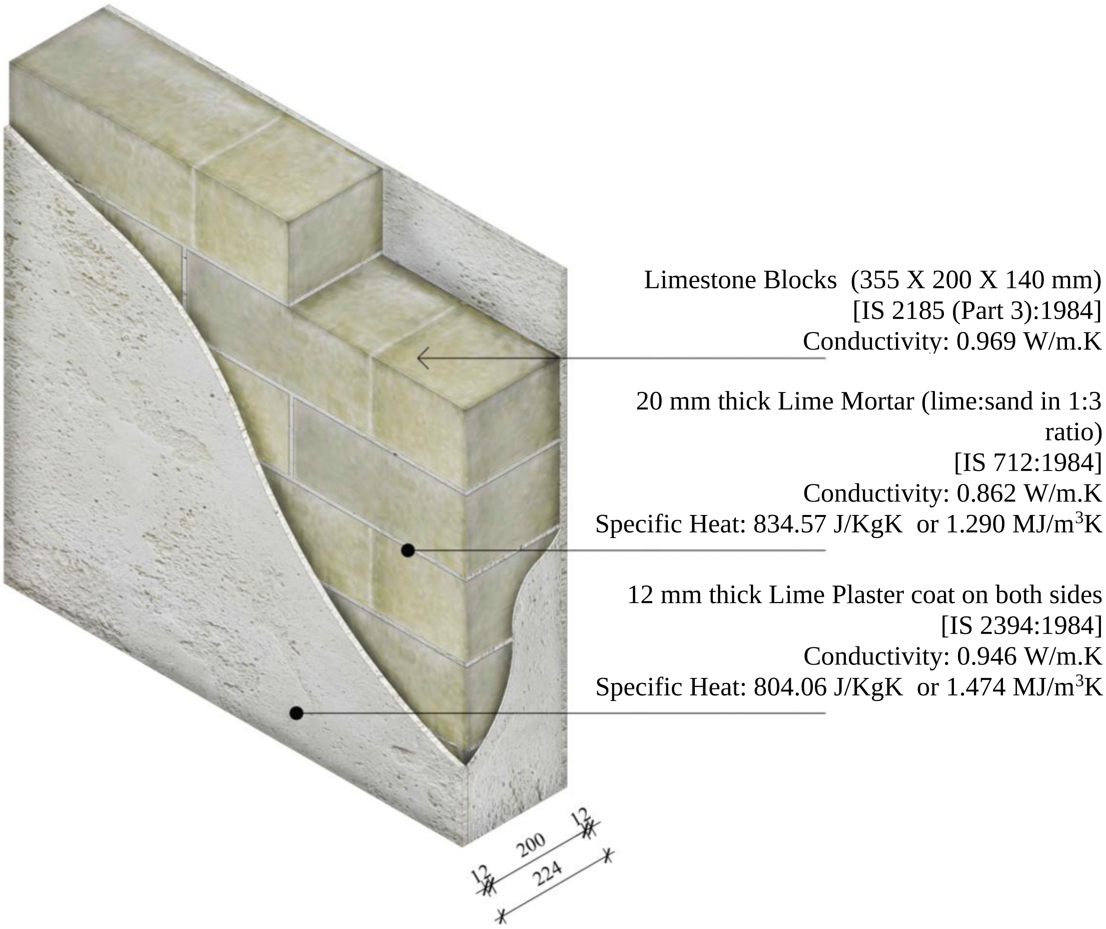


Figure 59: 3D Illustration of limestone wall with lime mortar and lime plaster

Figure 60: Preparation of limestone wall with lime mortar and lime plaster.

21. Limestone Wall with Cement Mortar and Cement Plaster

Limestone can be processed to produce blocks, bricks or powder. The powdered form is used to make mortar and plaster mix. It is a key ingredient in the manufacture of Portland cement or concrete. Limestone wall can be constructed with lime or cement mortar.

For the purpose of this research limestone blocks of size 355 mm x 200mm x 140mm were sourced from Junagadh. The materials were transported to the lab and the wall was constructed in the GHB specimen as seen in Figure 62. Cement mortar was applied to fix the blocks on the sample holder frame. The blocks were then laid on the wet mortar to align and set easily by allowing some movement during the construction. The cement to sand ratio used to prepare the cement mortar applied between the blocks was 1:4. The wall was left for 24 hours for the mortar to dry. Next, the cement plaster was prepared in the same ratio (1:4) and applied to finish the wall surface. The completed sample was left to dry for 10 days before thermal imaging and testing began. The illustration in plan and elevation is available in Annexure 2.

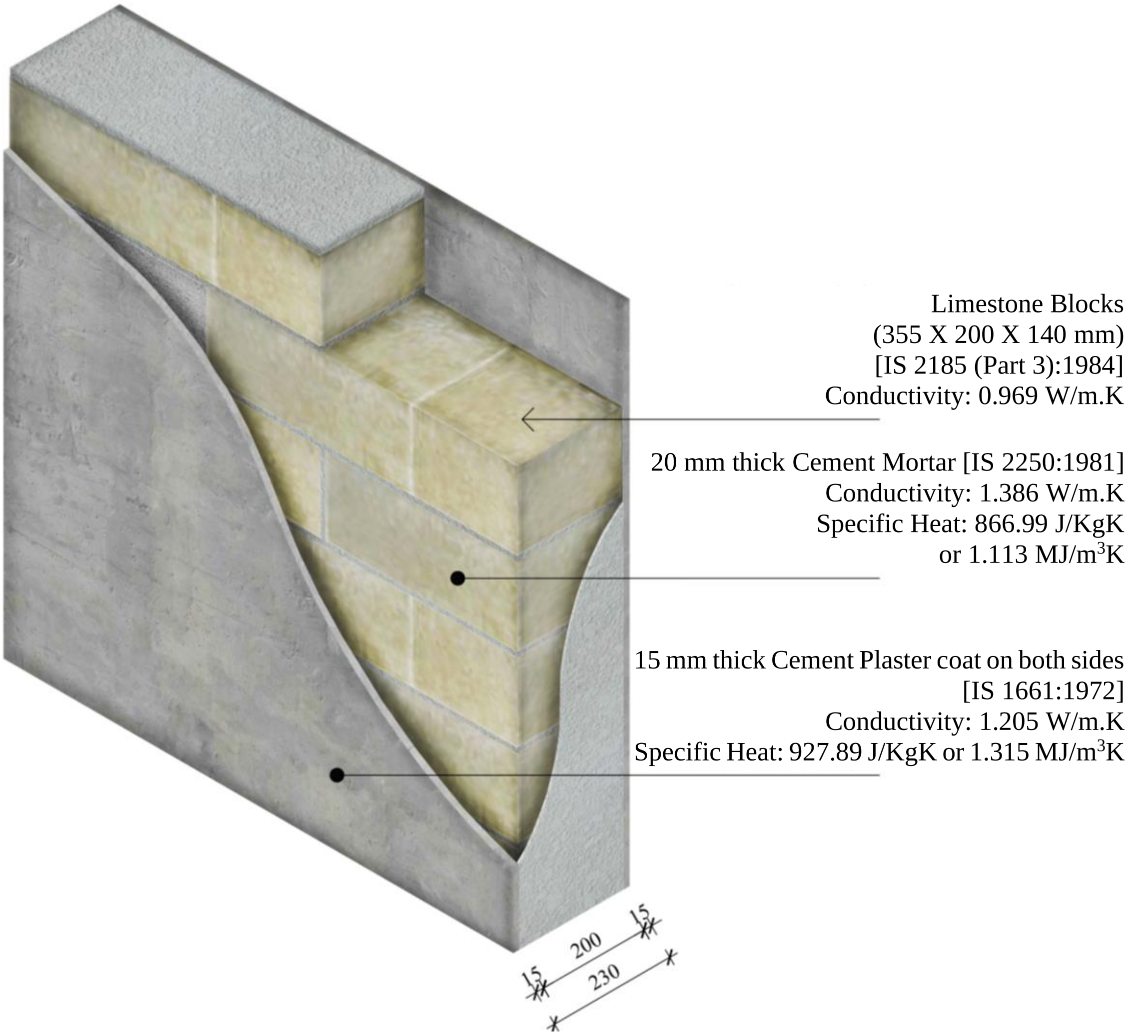


Figure 61: 3D Illustration of limestone wall with cement mortar and cement plaster

Figure 62: Preparation of limestone wall with cement mortar and cement plaster

22. Hollow clay brick (100mm thick) wall with cement plaster

Hollow clay bricks contain designed air gaps which significantly reduce the construction material and hence, the dead load. They are manufactured using natural additives such as coal ash, rice husk, and saw dust along with clay sourced from dead water tanks. Hollow clay brick walls can be constructed using either cement mortar (1:4 ratio for 100 mm thick walls) or a special kind of dry adhesive manufactured especially for tightly fixing the hollow bricks in wall. These bricks can be be chiselled for fixing electrical or plumbing conduits.

For this technology hollow clay bricks of full size- 400 mm x 200mm x 100mm and half size- 200 mm x 200 mm x 100 mm were sourced from Bengaluru. The materials were transported to the lab and the wall was constructed in the GHB specimen as seen in Figure 64. The blocks were laid with dry adhesive applied using a dispenser. The same was used to fix the blocks on the sample holder frame. The cement plaster was prepared in the 1:1 ratio and applied to finish the wall surface. The illustration in plan and elevation is available in Annexure 2.

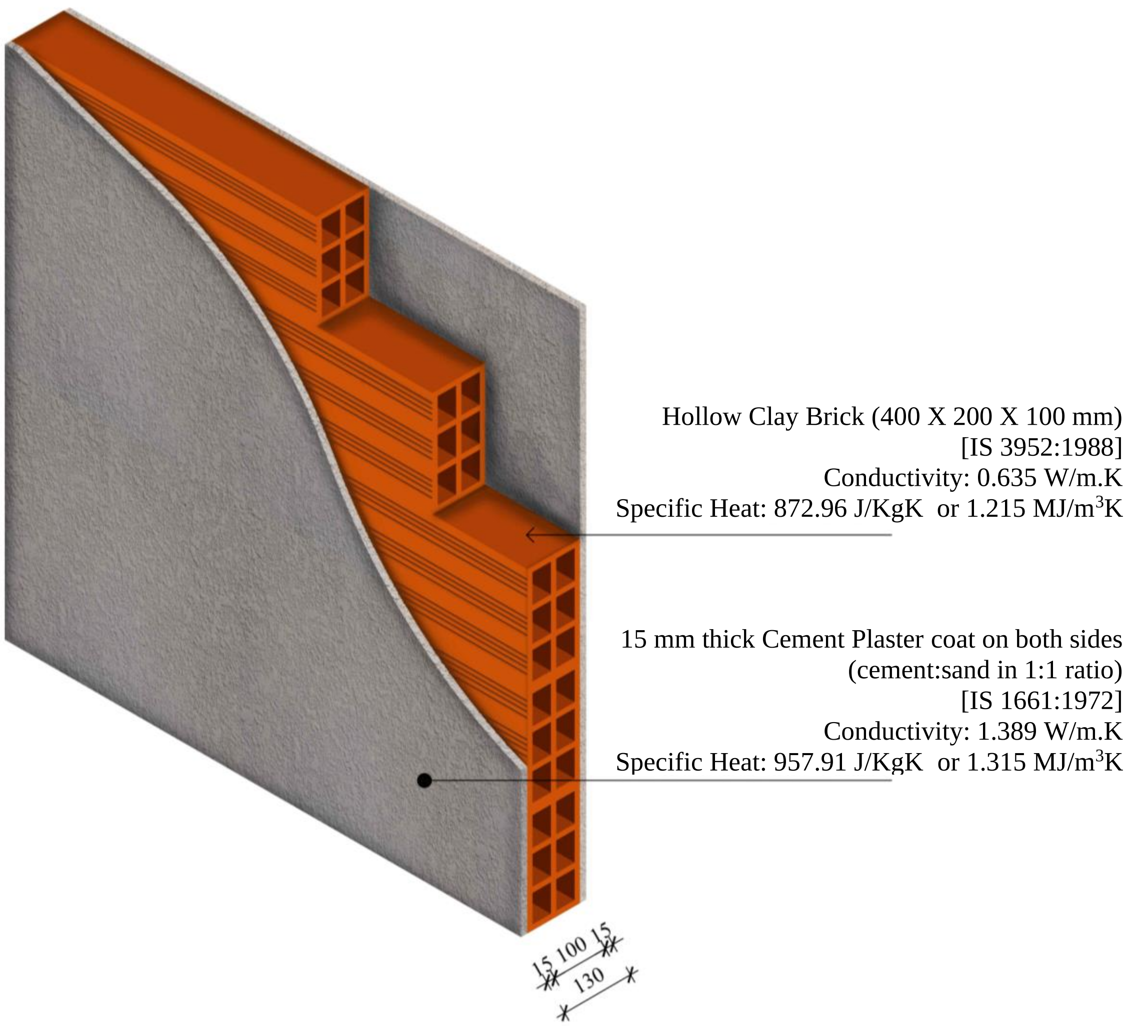


Figure 63: 3D Illustration of hollow clay brick wall (100 mm thick) with cement plaster on both sides

Figure 64: Preparation of hollow clay brick wall with cement plaster on both sides

23. Hollow clay brick (100mm thick) wall with XPS insulation

Extruded Polysterene insulation is manufactured through extrusion process, which allows the XPS sheet or board to have a smooth finish on both top and bottom sides. Moreover, the extrusion process gives the board a closed cell structure which may help in moisture resistance. XPS boards are available in various thicknesses and compressive strengths.

For this technology hollow clay bricks of full size- 400 mm x 200mm x 100mm and half size- 200 mm x 200 mm x 100 mm were sourced from Bengaluru. The materials were transported to the lab and the wall was constructed in the GHB specimen as seen in Figure 66. The blocks were laid with dry adhesive applied using a dispenser. The same was used to fix the blocks on the sample holder frame. The cement plaster was prepared in the 1:1 ratio and applied to the wall surface. The XPS board was fixed on the plaster coat using PVC film and finished with cement screed. The illustration in plan and elevation is available in Annexure 2.

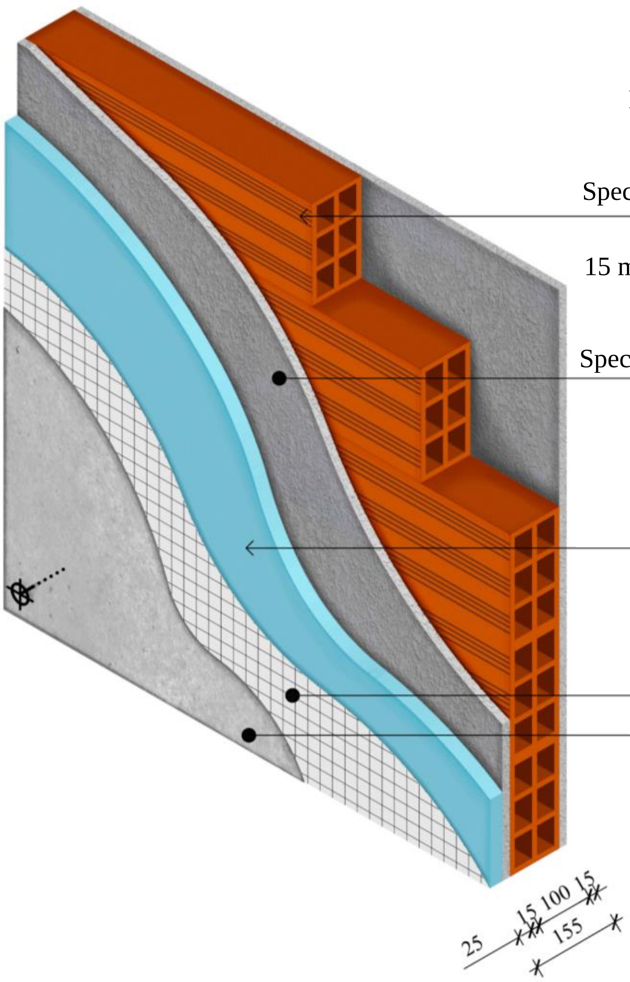


Figure 65: 3D Illustration of hollow clay brick wall (100 mm thick) with XPS insulation on one side

Figure 66: Preparation of hollow clay brick wall with cement plaster on both sides and XPS insulation on one side

24. Hollow clay brick (200mm thick) wall with rockwool insulation infill

Hollow clay bricks contain designed air gaps which significantly reduce the construction material and hence, the dead load. The air gaps can be used to infill rockwool insulation to increase thermal resistance of the walling technology. Rockwool or mineral wool is manufactured from a mix of volcanic rock and slag obtained as byproduct from steel manufacturing industry.

For this technology hollow clay bricks of full size- 400 mm x 200mm x 100mm and half size- 200 mm x 200 mm x 100 mm were sourced from Bengaluru. The blocks were filled with rockwool insulation sourced locally in Ahmedabad. The wall was constructed in the GHB specimen with rockwool-infilled clay bricks as seen in Figure 68. The blocks were laid with dry adhesive applied using a dispenser. The cement plaster was prepared in the 1:1 ratio and applied to finish the wall surface. The illustration in plan and elevation is available in Annexure 2.

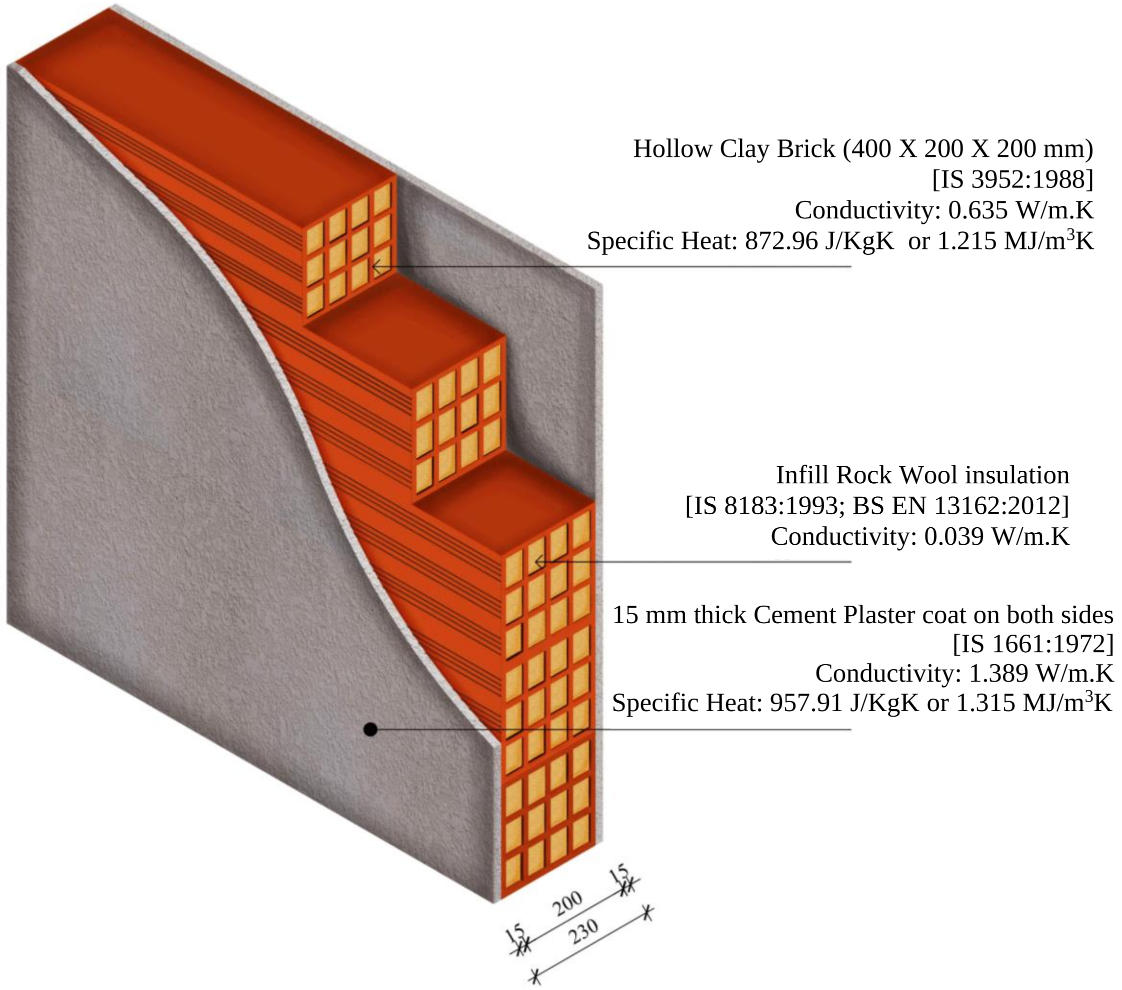


Figure 67 : 3D Illustration of hollow clay brick wall (200 mm thick) with rockwool insulation infill

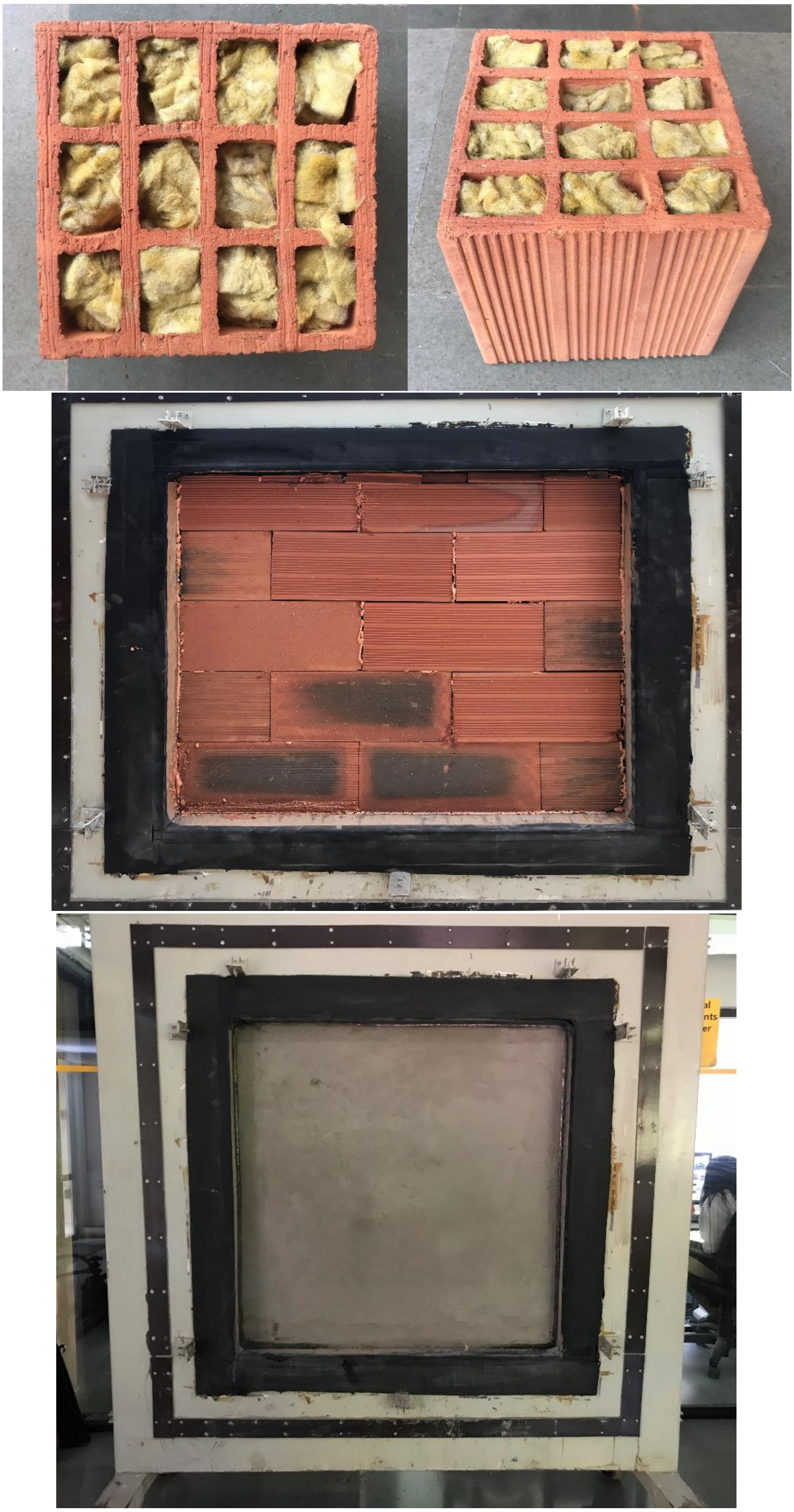


Figure 68: Preparation of hollow clay brick wall with rockwool infill

25. Hollow clay brick (200mm thick) wall with cement plaster

Hollow clay bricks contain designed air gaps which significantly reduce the construction material and hence, the dead load. They are manufactured using natural additives such as coal ash, rice husk, and saw dust along with clay sourced from dead water tanks. Hollow clay brick walls can be constructed using either cement mortar (1:4 ratio for 100 mm thick walls) or a special kind of dry adhesive manufactured especially for tightly fixing the hollow bricks in wall. These bricks can be be chiselled for fixing electrical or plumbing conduits.

For this technology hollow clay bricks of full size- 400 mm x 200mm x 200mm and half size- 200 mm x 200 mm x 200 mm were sourced from Bengaluru. The materials were transported to the lab and the wall was constructed in the GHB specimen as seen in Figure 70. The blocks were laid with dry adhesive applied using a dispenser. The same was used to fix the blocks on the sample holder frame. The cement plaster was prepared in the 1:1 ratio and applied to finish the wall surface. The illustration in plan and elevation is available in Annexure 2.

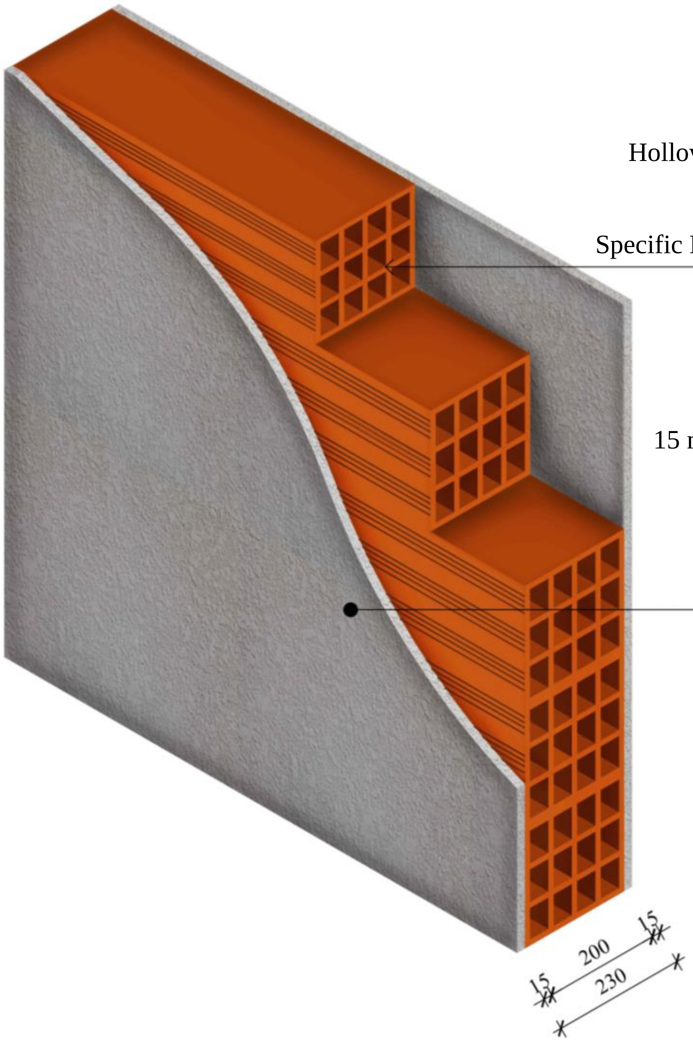


Figure 69: 3D Illustration of hollow clay brick wall (200 mm thick) with cement plaster on both sides

Figure 70: Preparation of hollow clay brick wall with rockwool infill

26. Hollow clay brick (200mm thick) wall with XPS insulation

Extruded Polysterene insulation is manufactured through extrusion process, which allows the XPS sheet or board to have a smooth finish on both top and bottom sides. Moreover, the extrusion process gives the board a closed cell structure which may help in moisture resistance. XPS boards are available in various thicknesses and compressive strengths.

For this technology hollow clay bricks of full size- 400 mm x 200mm x 200mm and half size- 200 mm x 200 mm x 200 mm were sourced from Bengaluru. The materials were transported to the lab and the wall was constructed in the GHB specimen as seen in Figure 72. The blocks were laid with dry adhesive applied using a dispenser. The same was used to fix the blocks on the sample holder frame. The cement plaster was prepared in the 1:1 ratio and applied to the wall surface. The XPS board was fixed on the plaster coat using PVC film and finished with cement screed. The illustration in plan and elevation is available in Annexure 2.

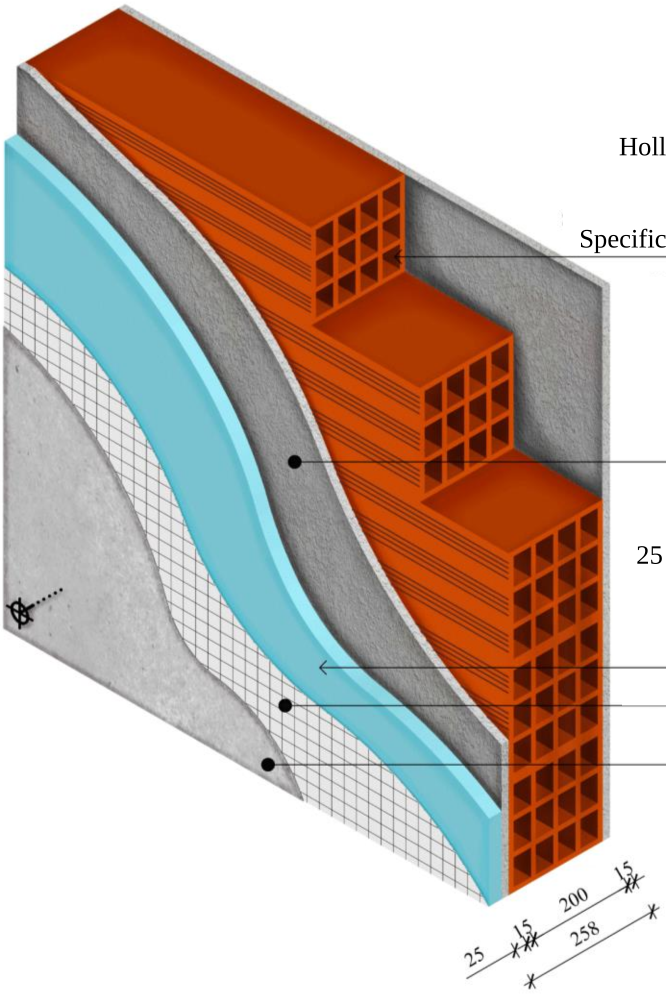


Figure 71: 3D Illustration of hollow clay brick walls (200 mm thick) with XPS insulation on one side

Figure 72: Preparation of hollow clay brick wall (200mm thick) with XPS insulation

27. RCC wall

Reinforced Cement Concrete (RCC) walls are the most common walls in business as usual construction. The cement concrete provides compressive strength to the walll while reinforcement i.e. steel bars provides tensile strength. This assembly was included in testing to allow for two reasons:

- It allows for comparison between RCC-based technologies with varying insulating materials.
- It is representative of the walling technologies achieved through emerging construction techniques such as tunnel formwork, precast concrete construction, etc which allow faster construction. The constituents of concrete can be varied based on desired performance.

The RCC wall sample was constructed using RCC blocks with vertical and horizontal reinforcements i.e. steel bars of 8 mm diameter placed 110 mm apart, outside the sample. The blocks were then installed in the GHB sample holder as shown in Figure 74. The illustration in plan and elevation is available in Annexure 2.

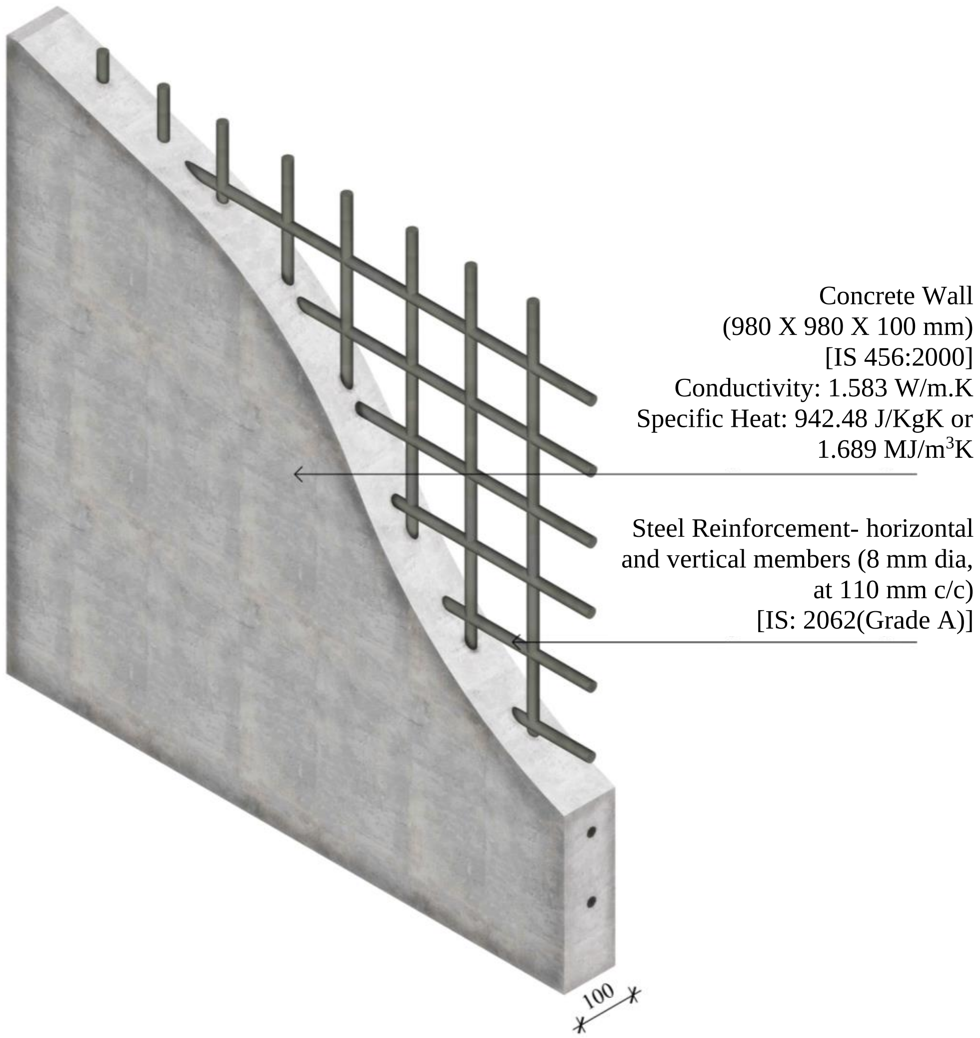


Figure 73: 3D Illustration of 100 mm thick RCC wall

Figure 74: Preparation of 100mm thick RCC wall

28. RCC wall with EPS

Expanded Polystyrene or EPS board is a solid insulating material used in walls to improve thermal performance of the technologies. EPS boards are manufactured by expanding polystyrene beads into foam using heat or steam. Desirable sizes of boards are obtained by shaping the product during expansion and cutting them using heated nichrome wires to give a smooth finish.

The RCC wall sample was constructed using RCC blocks with vertical and horizontal reinforcements i.e. steel bars of 8 mm diameter placed 110 mm apart, outside the sample. The blocks were then installed in the GHB sample holder as shown in Figure 76. Further EPS board was fixed to one side of the wall. Figure 76 shows the process of constructing RCC wall sample in the GHB samaple holder. The illustration in plan and elevation is available in Annexure 2.

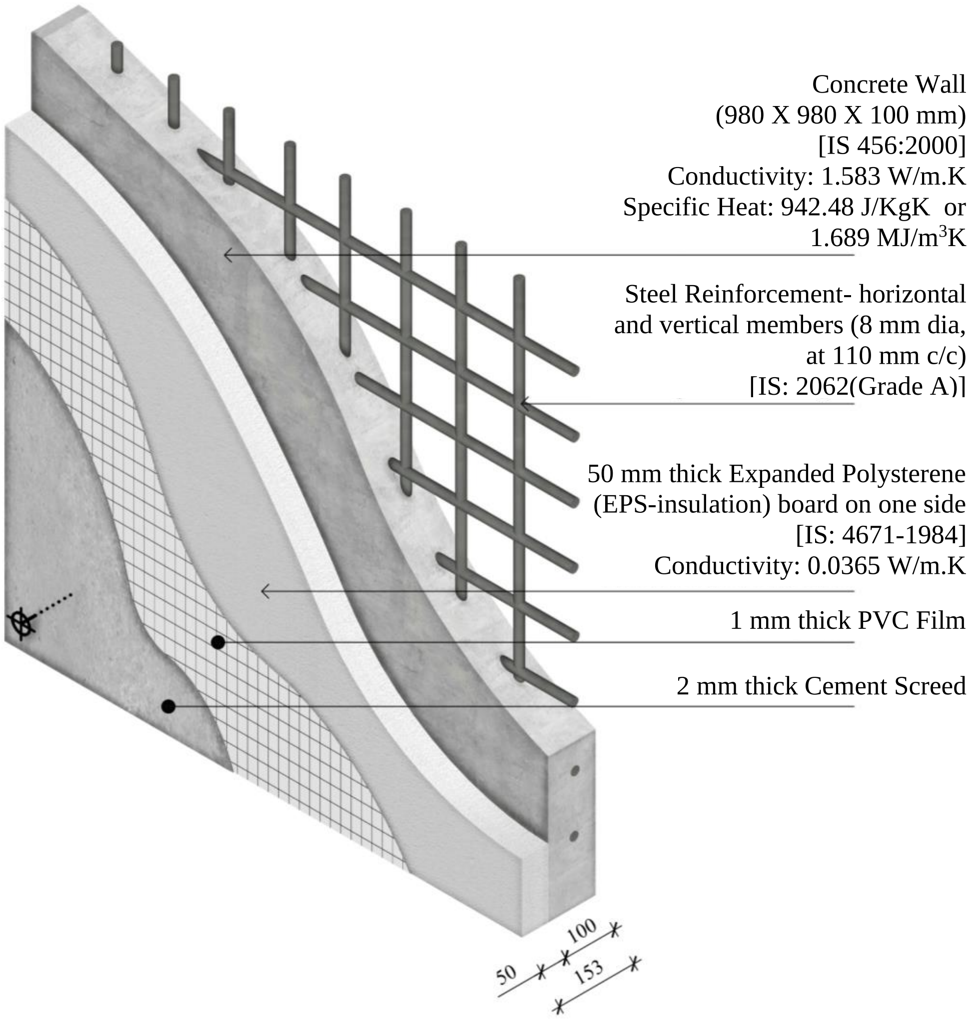


Figure 75: 3D Illustration of RCC wall with EPS board on one side

Figure 76: Preparation of RCC wall with EPS board on one side

29. RCC wall with Styrofoam (EPS) board on both sides

Styrofoam (EPS) is commonly used in packaging products, coffee cups, etc. These are manufactures in the same way as EPS boards i.e. by expanding polymer beads. They are available in varying options of thermal performances (i.e. thermal conductivity) and thicknesses.

The RCC wall sample was constructed using RCC blocks with vertical and horizontal reinforcements i.e. steel bars of 8 mm diameter placed 110 mm apart, outside the sample. The blocks were then installed in the GHB sample holder as shown in Figure 78. Further Styrofoam (EPS) boards were fixed to both sides of the wall. Figure 78 shows the process of constructing RCC wall sample in the GHB samaple holder. The illustration in plan and elevation is available in Annexure 2.

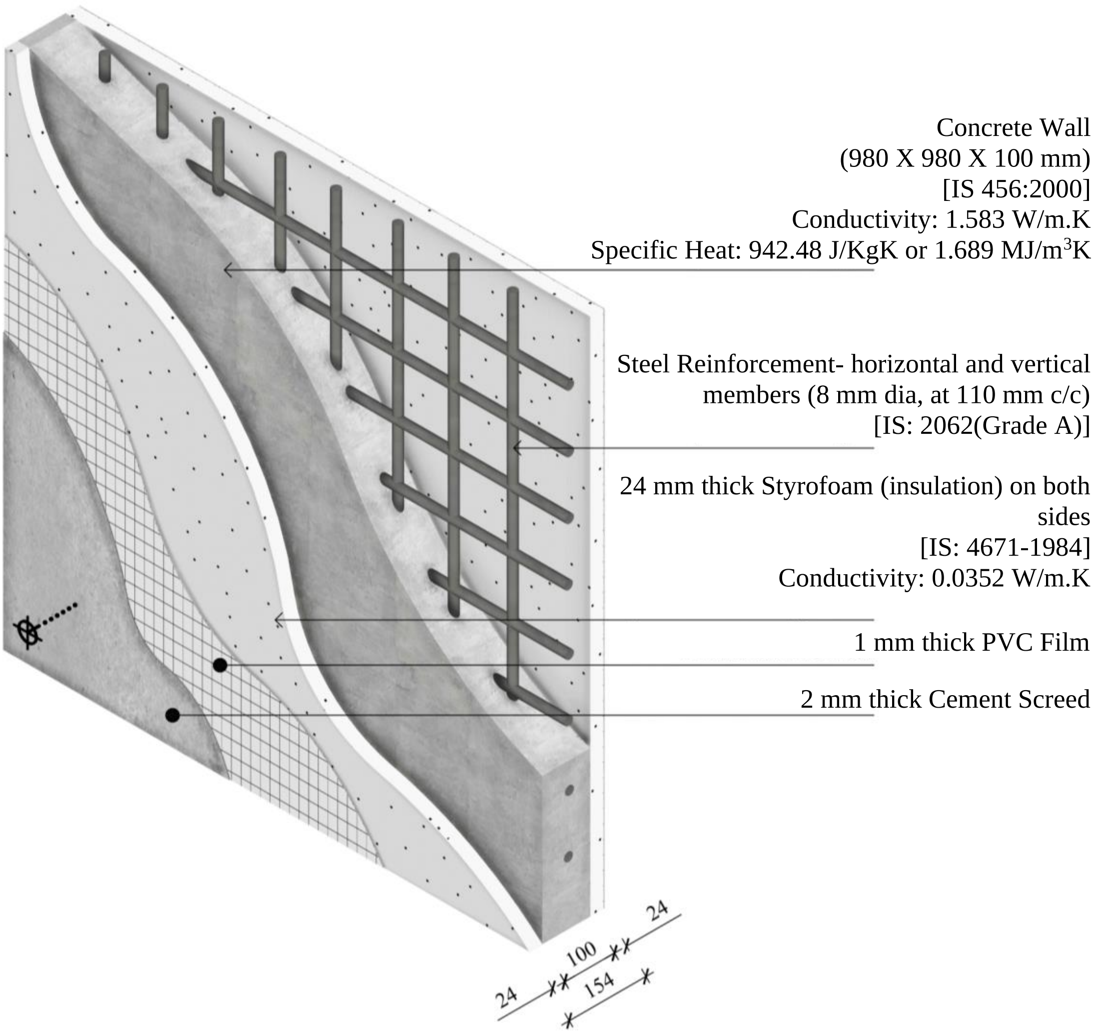


Figure 77: 3D Illustration of RCC wall with Styrofoam (EPS) board on both sides

Figure 78: Preparation of RCC wall with Styrofoam (EPS) board on both sides

30. RCC Wall with PVC Panels on both sides

This walling technology is derived from the stay-in-place PVC formwork or SIP panels, where the pre-fabricated PVC wall forms are filled with concrete to construct RCC walls finished with PVC panels. The PVC panels provide a smooth finish for the walls, eliminating the need for plastering or other finishing coats.

The RCC wall sample was constructed using RCC blocks with vertical and horizontal reinforcements i.e. steel bars of 8 mm diameter placed 110 mm apart, outside the sample. The blocks were then installed in the GHB sample holder as shown in Figure 80. Further PVC panels were fixed to both sides of the wall. Figure 80 shows the process of constructing RCC wall sample in the GHB samaple holder. The illustration in plan and elevation is available in Annexure 2.

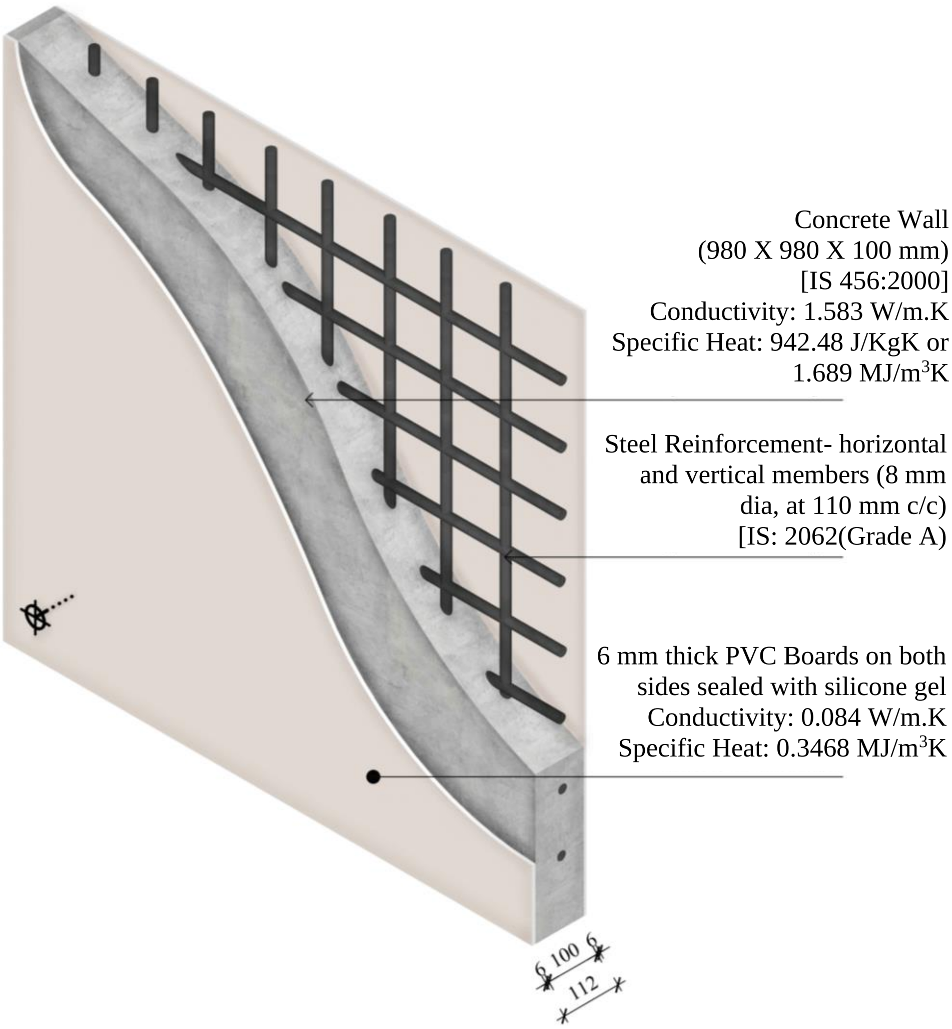


Figure 79: 3D Illustration of RCC wall with PVC panels on both sides

Figure 80: Preparation of RCC wall with PVC panels on both sides

31. RCC Wall with EPS Board on one side and PVC panels on both sides

This walling technology is derived from pre-fabricated sandwich panel systems that consists of a core material sandwiched between two face boards. The core material consists of RCC while the face boards could be made of fibre-cement, PVC panels, or calcium silicate boards. Further, insulation can be added to this assembly in the form of either EPS granule balls in the core material or as EPS board finished with cement screed.

The RCC wall sample was constructed using RCC blocks with vertical and horizontal reinforcements i.e. steel bars of 8 mm diameter placed 110 mm apart, outside the sample. The blocks were then installed in the GHB sample holder as shown in Figure 82. Further PVC panels were fixed to both sides of the wall and EPS sheet to only one side. Figure 82 shows the process of constructing RCC wall sample in the GHB samaple holder. The illustration in plan and elevation is available in Annexure 2.

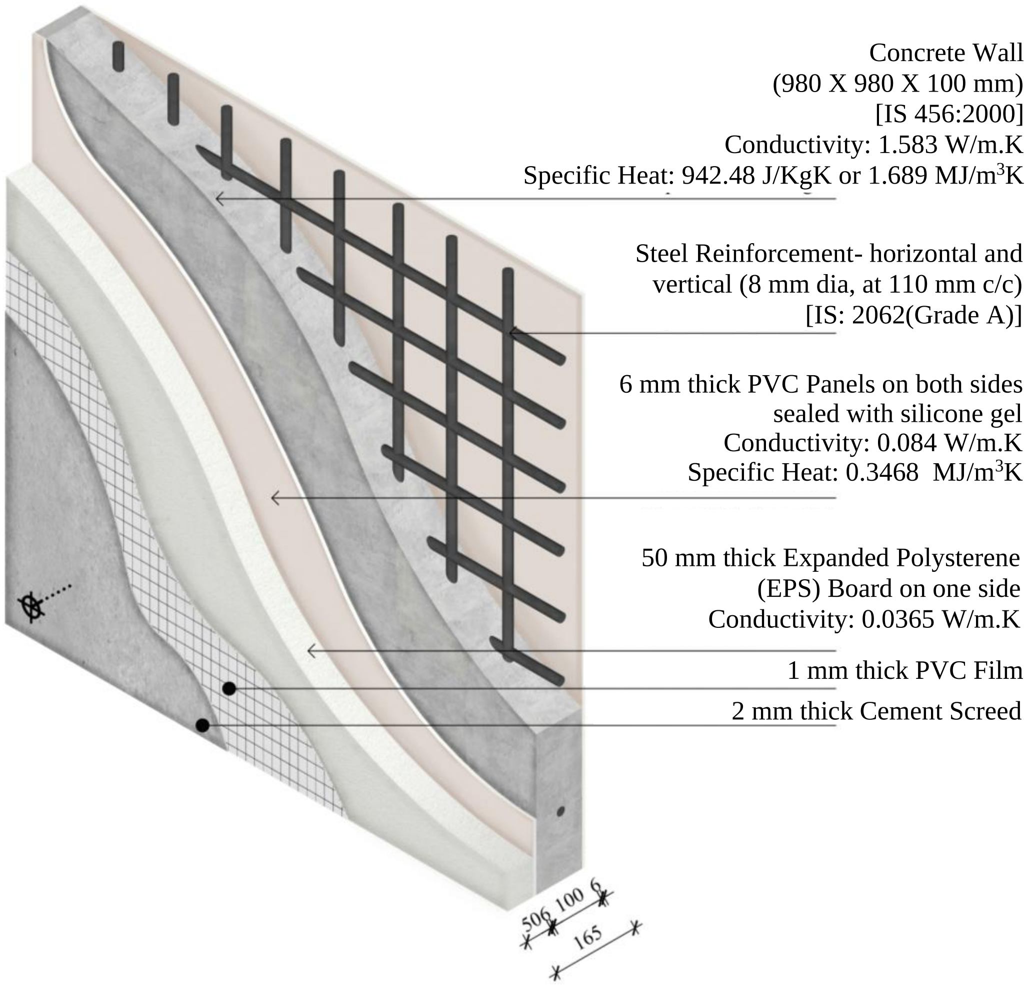


Figure 81: 3D Illustration of RCC wall with EPS board and PVC panels on both sides

Figure 82: Preparation of RCC wall with EPS board on one side and PVC panels on both sides

Annexure II: Schematic Drawings of the Test Samples

1. Rat-trap bond wall.

Total wall thickness= 250 mm
U value of the assembly= 2.11 W/m^{2}K

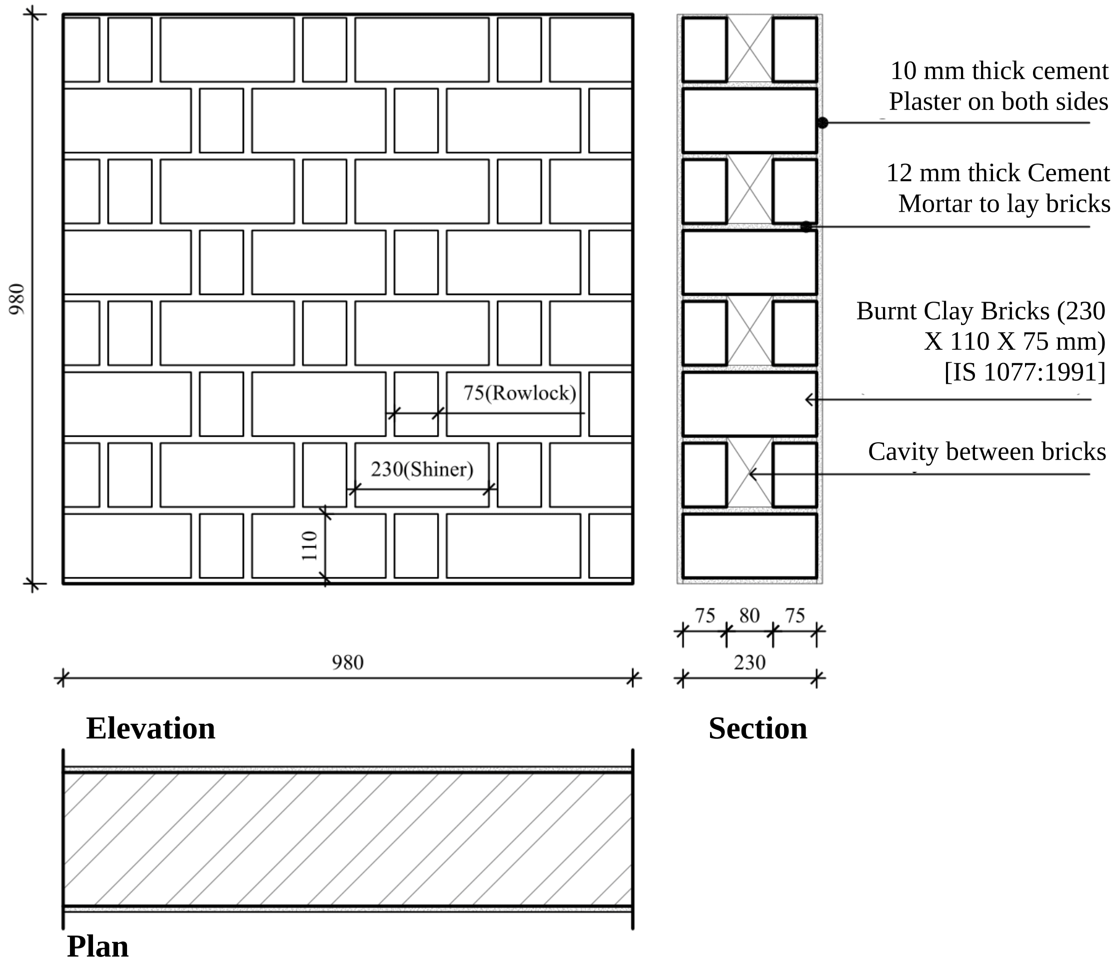


Figure 83: Schematic drawings of Rat-trap bond wall

Table 5: Walling technology and testing details for Rat-trap bond wall

Layers	Dimensions	Specification	Properties		Testing Method	
			Conductivity	Specific heat	Particulars	Total Wall assembly
Cement Plaster mix (for both sides)	10 mm thick (cement : sand in 1:1 ratio)	IS 1661:1972	-			
Cement Mortar mix	12 mm thick (cement: sand in 1:1 ratio)	IS 2250:1981				ASTM C 1363
Burnt Clay Bricks	230 X 110 X 75 in mm	IS 1077:1991				

2. Light Guage Framed Steel Structure (LGFSS)

a. LGFSS with Expanded Polysterene (EPS) board with Guniting on one side and Gypsum Board on other side

Total wall thickness= 136 mm

U value of the assembly= 1.37 W/m^{2}K

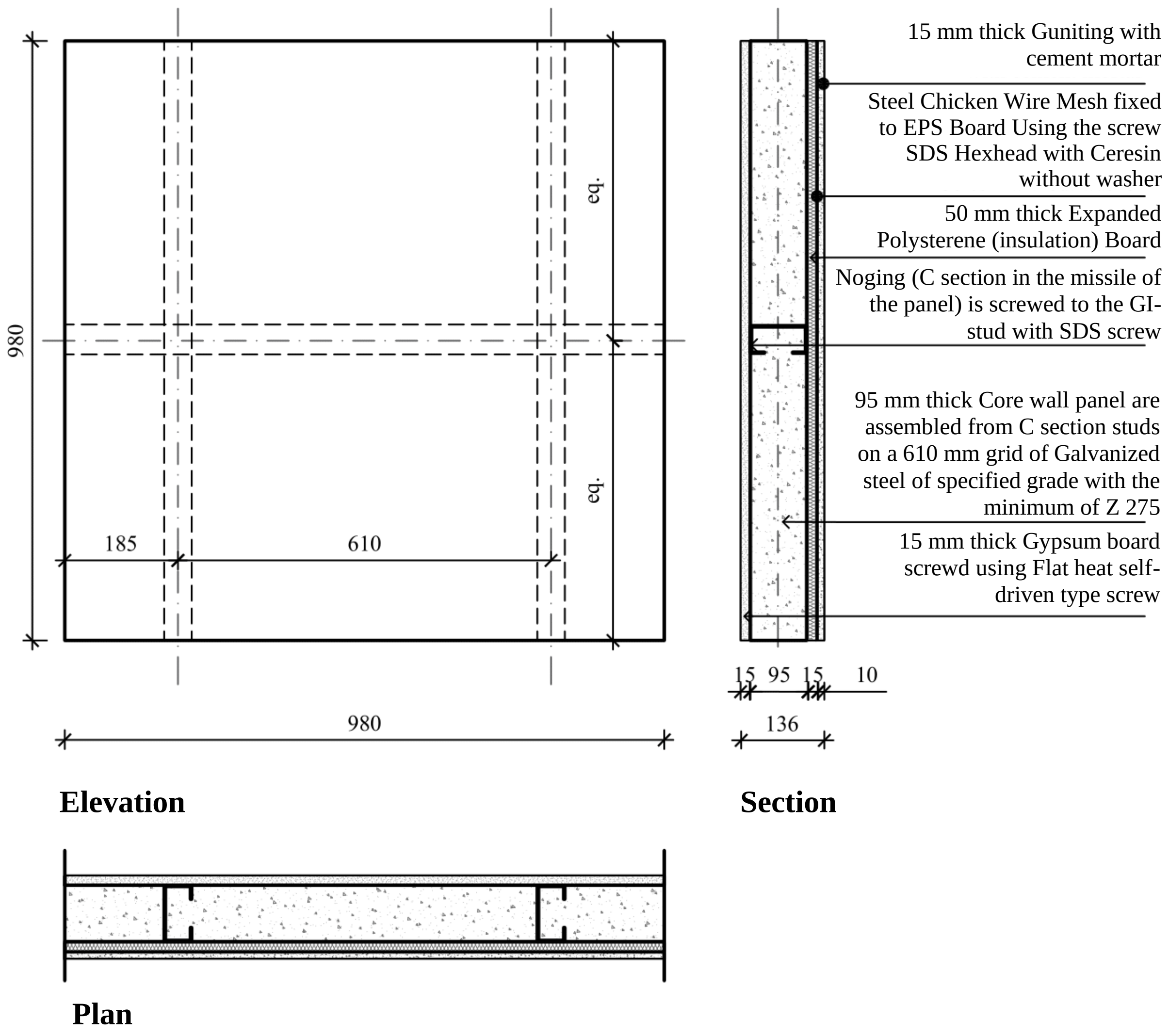


Figure 84 : Schematic drawings of LGFSS wall sample: External wall type 1 with EPS as per specifications and drawings found in BMTPC Performance appraisal certificate (PAC) no: 1014-S/2014.

Table 6 : Walling technology and testing details for LGFSS wall sample with EPS board

Particulars	Dimensions	Specification	Properties		Testing Method	
			Conductivity	Specific heat	Particulars	Total Wall assembly
Cement Plaster mix for Guniting	10 mm thick (cement : sand in 1:1 ratio)	IS 9012:1978				ASTM C 1363
Steel Chicken Wire mesh	4 mm dia wire of UTS 480 MPa of spacing 150 x 150 mm or 1.4 mm dia of spacing 40 x 40 mm.	IS 3150:1982				
Expanded Polysterene (EPS) Board	15 mm thick	IS 4671:1984				
Concrete mix (for core wall panel)	95 mm thick	IS 456:2000				
Steel C Section (Nogging)		ASTM A 653A, 653/M:2013, IS 277:1992				
Gysum Board	15 mm thick	IS 2095 (Part-I): 2011				

b. LGFSS with Pre-Painted Galvanized Iron (PPGI) sheet

Total wall thickness= 150 mm,
U value of the assembly= 2.12 W/m^{2}K

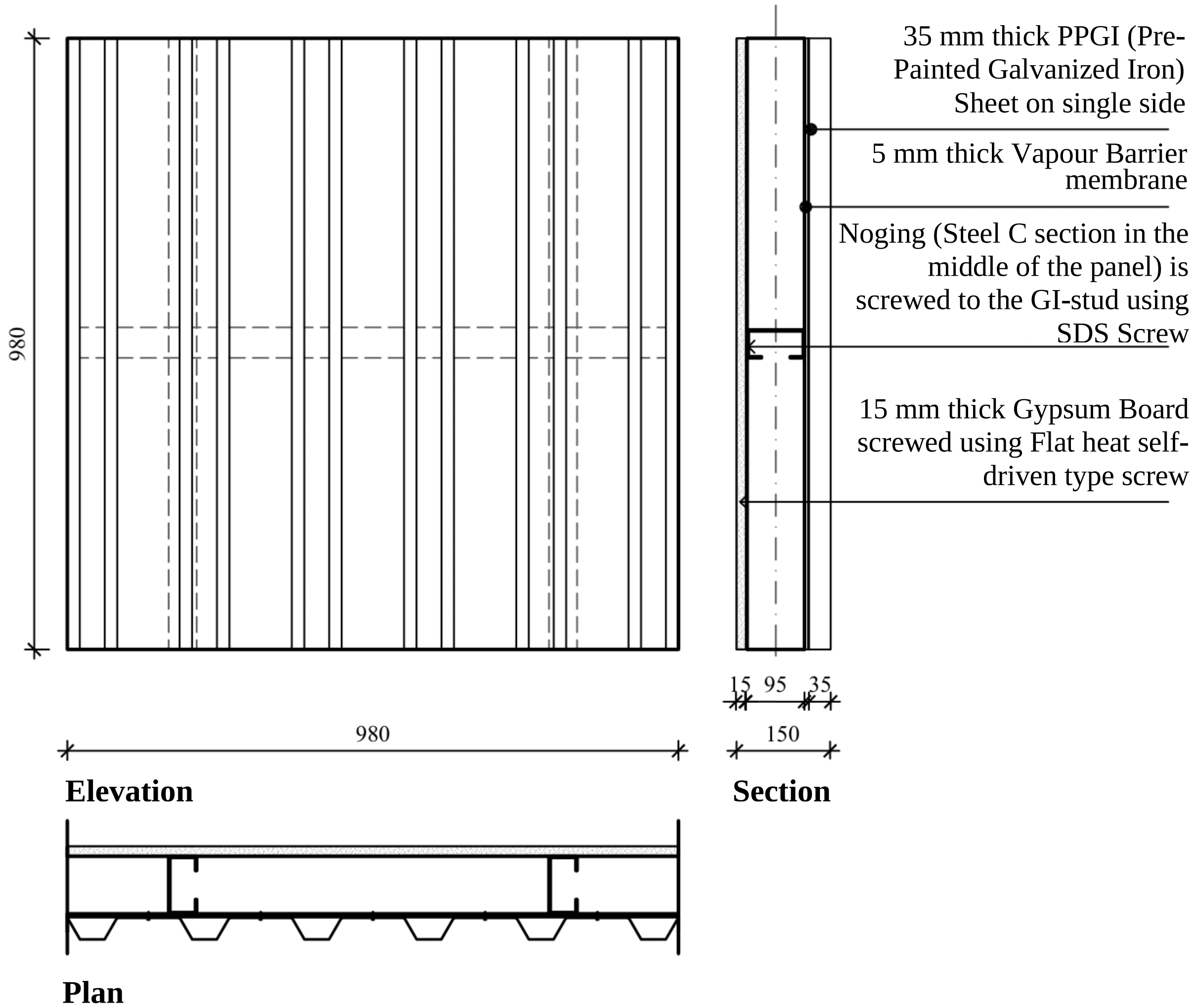


Figure 85: Schematic drawings of LGFSS wall sample with PPGI sheet as per specifications and drawings found in BMTPC Performance appraisal certificate (PAC) no:1014-S/2014.

Table 7 : Walling technology and testing details for LGFSS wall sample with PPGI sheet

Particulars	Dimensions	Specification	Properties		Testing Method	
			Conductivity	Specific heat	Particulars	Total Wall assembly
Pre- Painted Galvanized Iron (PPGI) sheet	35 mm thick	IS 14246:1995				
Vapor Barrier membrane	5 mm thick	ASTM E1745				ASTM C 1363
Steel C Section (Nogging)	On a 610 mm grid of Galvanized steel of	ASTM A 653A, 653/M:2013, IS 277:1992				

	specified grade.	
Gysum Board	15 mm thick	IS 2095 (Part-I): 2011

3. Reinforced Expanded Polystyrene (EPS) Core Panel System

Total wall thickness= 150 mm

U value of the assembly= 0.56 W/m^{2}K

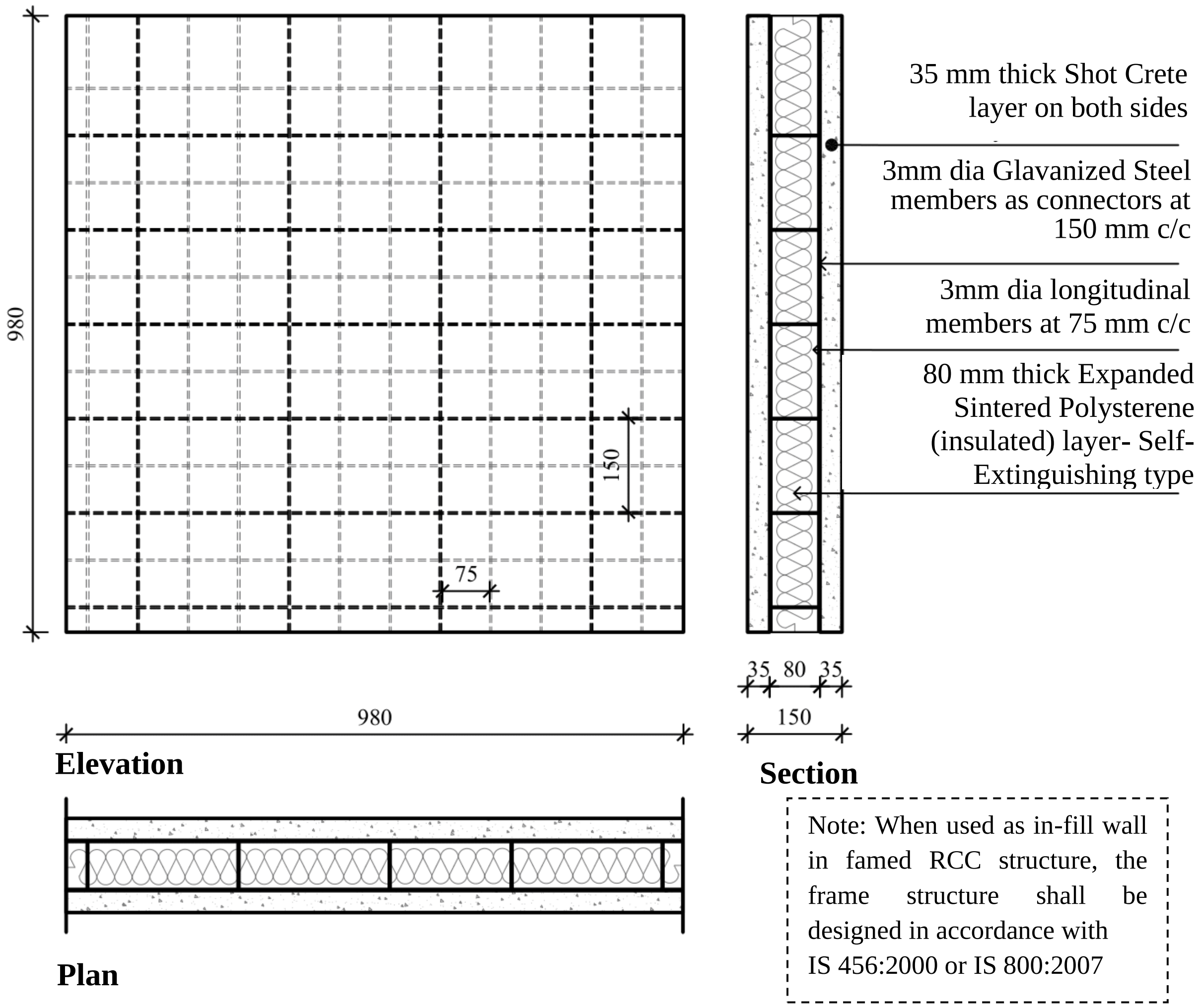


Figure 86 : Schematic drawings of Reinforced EPS core panel wall sample as per specifications and drawings found in the BMTPC Performance Appraisal Certificate (PAC) no: 1020-S/2015.

Table 8: Walling technology and testing details for Reinforced EPS core panel wall

Particulars	Dimensions	Specification	Properties		Testing Method	
			Conductivity	Specific heat	Particulars	Total Wall assembly
Shotcrete Mix (for both sides)	35 mm thick	IS 9012:1978				ASTM C 1363
Galvanized Steel members	3 mm dia	IS : 432 (Part I)- 1982;				

(tranverse, longitudinal)	(at 75 mm c/c, 150 c/c)	
Expanded Polysteren (EPS) Board-Sintered	80 mm thick (Self-Extinguishing type)	IS 4671:1984

4. Glass Fibre Reinforced Gypsum (GFRG) Panel

c. Unfilled

Total wall thickness= 124 mm

U value of the assembly= 2.06 W/m^{2}K

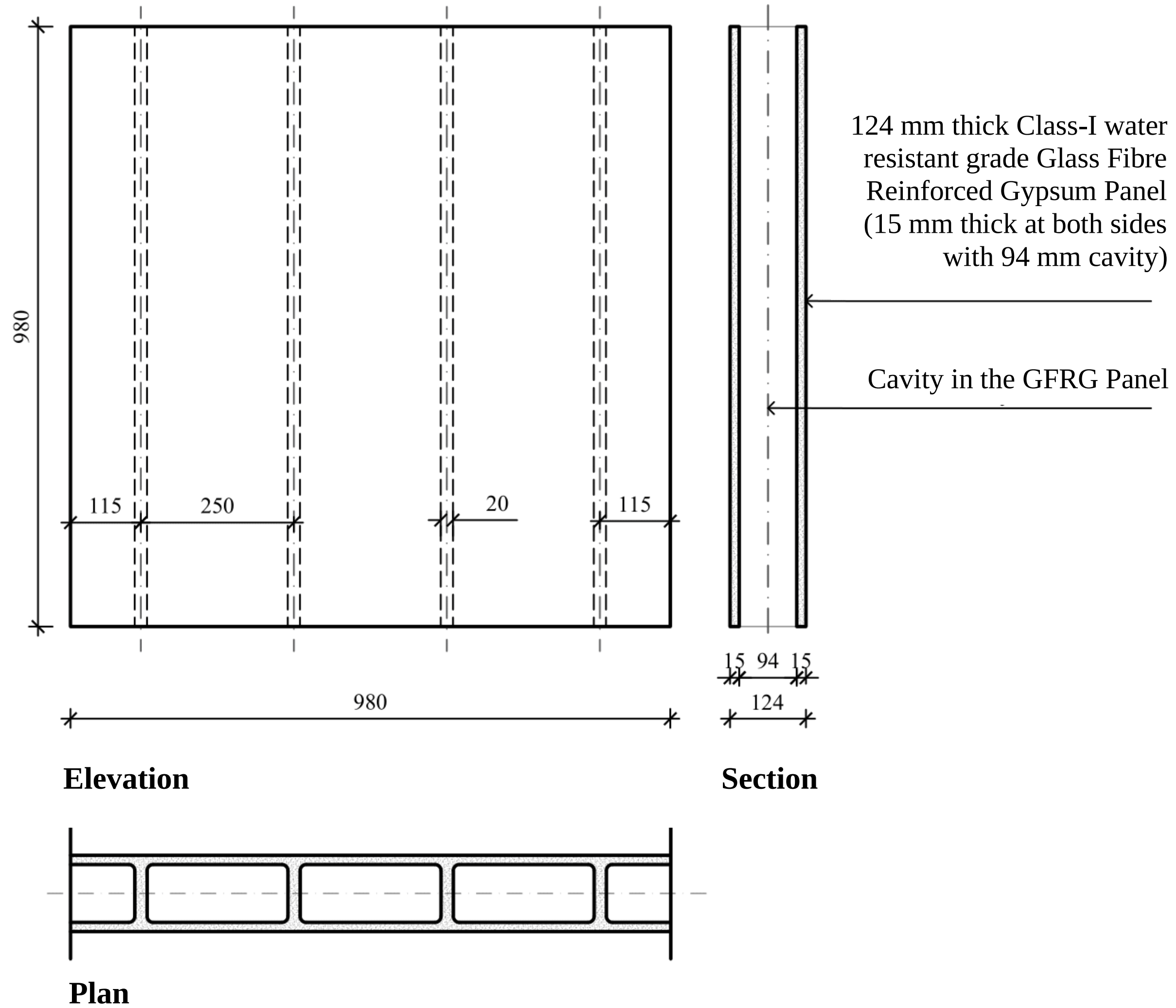


Figure 87: Schematic drawings of Glass Fibre Reinforced Gypsum building Panel wall sample; Class-1 unfilled panel, as per specifications and drawings found in BMTPC Performance Appraisal Certificate (PAC) no: 1009-S/2012 and structural design manual.

Table 9: Walling technology and testing details for GFRG Panel wall- unfilled

Particulars	Dimensions	Specification	Properties		Testing Method	
			Conductivity	Specific heat	Particulars	Total Wall assembly
Class 1 Glass Fibre Reinforced Gypsum Panel (Water resistant)	124 mm thick (15 mm thick at both side with 94 mm cavity inside)	ASTM C1355/ C1355M-96 (2020)				ASTM C 1363

d. With RCC and non-structural filling

Total wall thickness= 124 mm

U value of the assembly= 2.12 W/m^{2}K

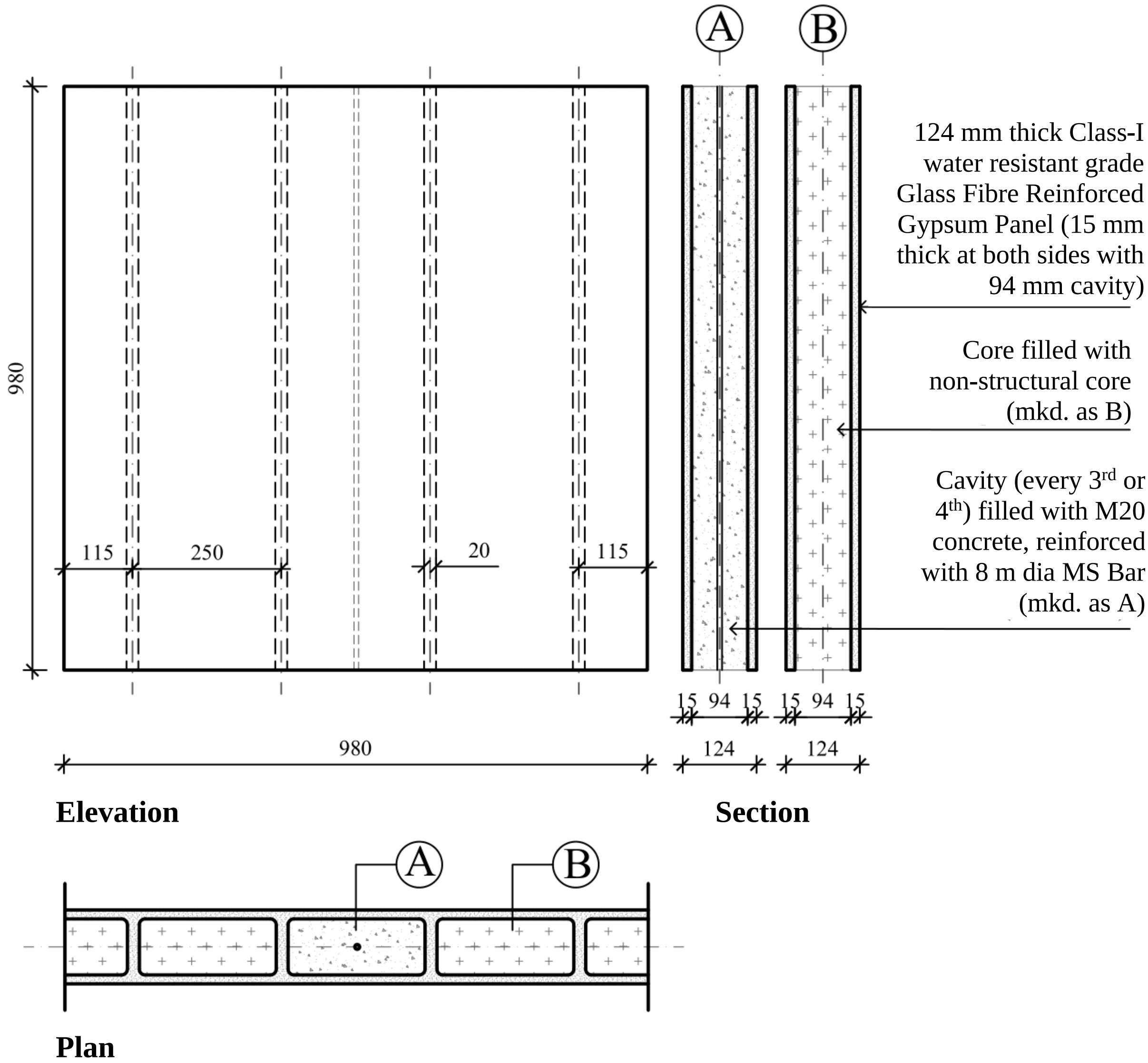


Figure 88 : Schematic drawings of Glass Fibre Reinforced Gypsum building Panel wall sample; Class-1 fully filled load-bearing panel as per specifications and drawings found in BMTPC Performance Appraisal Certificate (PAC) no: 1009-S/2012 and structural design manu

Table 10 : Walling technology and testing details for GFRG Panel wall- fully filled

Particulars	Dimensions	Specification	Properties		Testing Method	
			Conductivity	Specific heat	Particulars	Total Wall assembly
Class 1 Glass Fibre Reinforced Gypsum Panel (Water resistant)	124 mm thick (15 mm thick at both side with 94 mm cavity inside)	ASTM C1355/ C1355M-96 (2020)				ASTM C 1363
Cavity Filled with non-structural core filling	94 mm (as per drawing)					
Cavity (every 3rd or 4th) filled with M20 concrete, reinforced with 8mm dia MS Bar		IS 456:2000				

e. **Partial RCC filling**

Total wall thickness= 124 mm
U value of the assembly= 2.13 W/m^{2}K

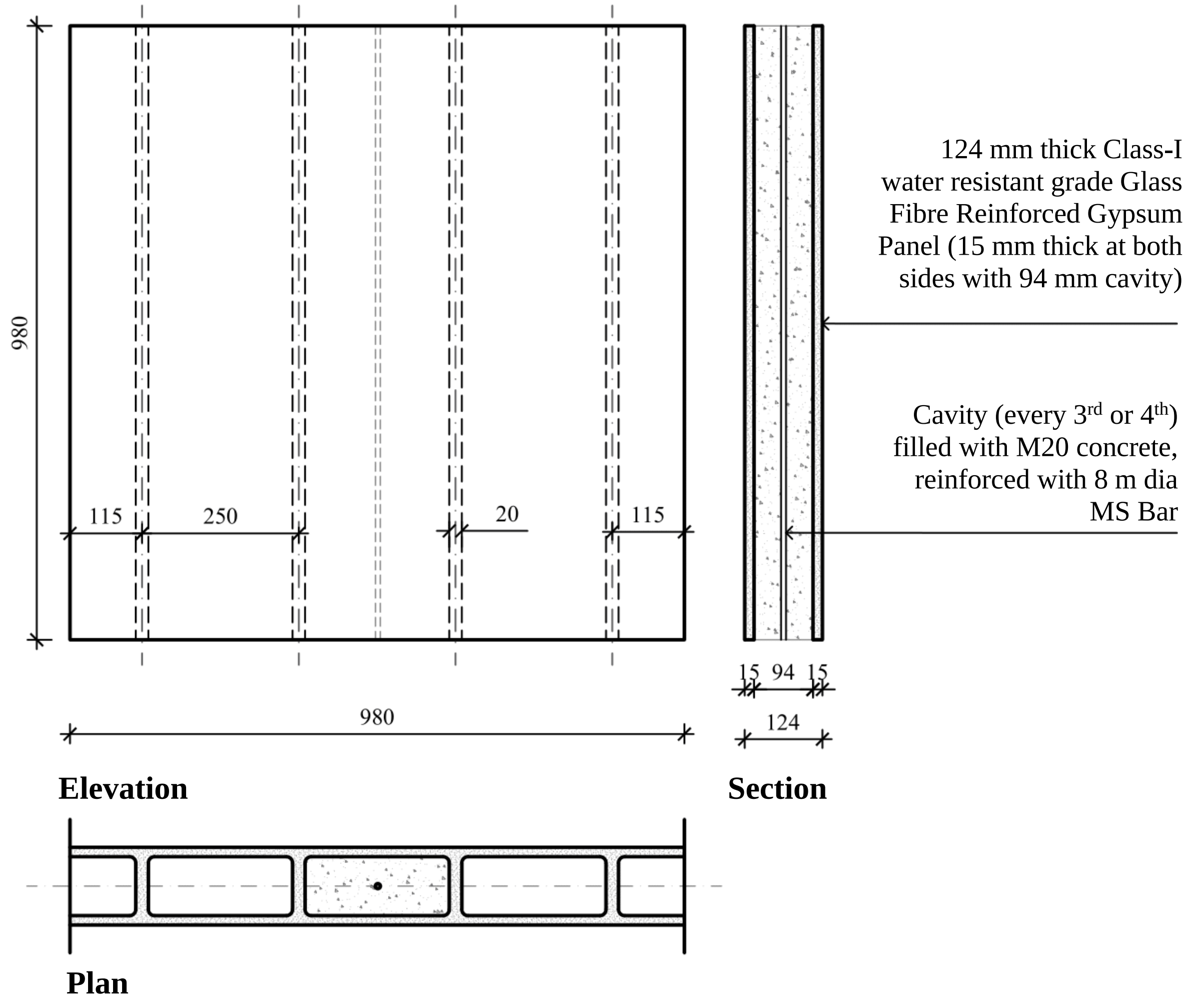


Figure 89 : Schematic drawings of Glass Fibre Reinforced Gypsum building Panel wall sample; Class-1 partially filled load-bearing panel with non-structural core filling as per specifications found in BMTPC Performance Appraisal Certificate (PAC) no: 1009-S/2012

Table 11 : Walling technology and testing details for GFRG Panel wall- partially filled

Particulars	Dimensions	Specification	Properties		Testing Method	
			Conductivity	Specific heat	Particulars	Total Wall assembly
Class 1 Glass Fibre Reinforced Gypsum Panel (Water resistant)	124 mm thick (15 mm thick at both side with 94 mm cavity inside)	ASTM C1355/ C1355M-96 (2020)				ASTM C 1363
Cavity (every 3rd or 4th) filled with M20 concrete, reinforced with 8mm dia MS Bar		IS 456:2000				

5. Burnt Clay Brick Wall

Total wall thickness= 250 mm

U value of the assembly= 2.41 W/m^{2}K

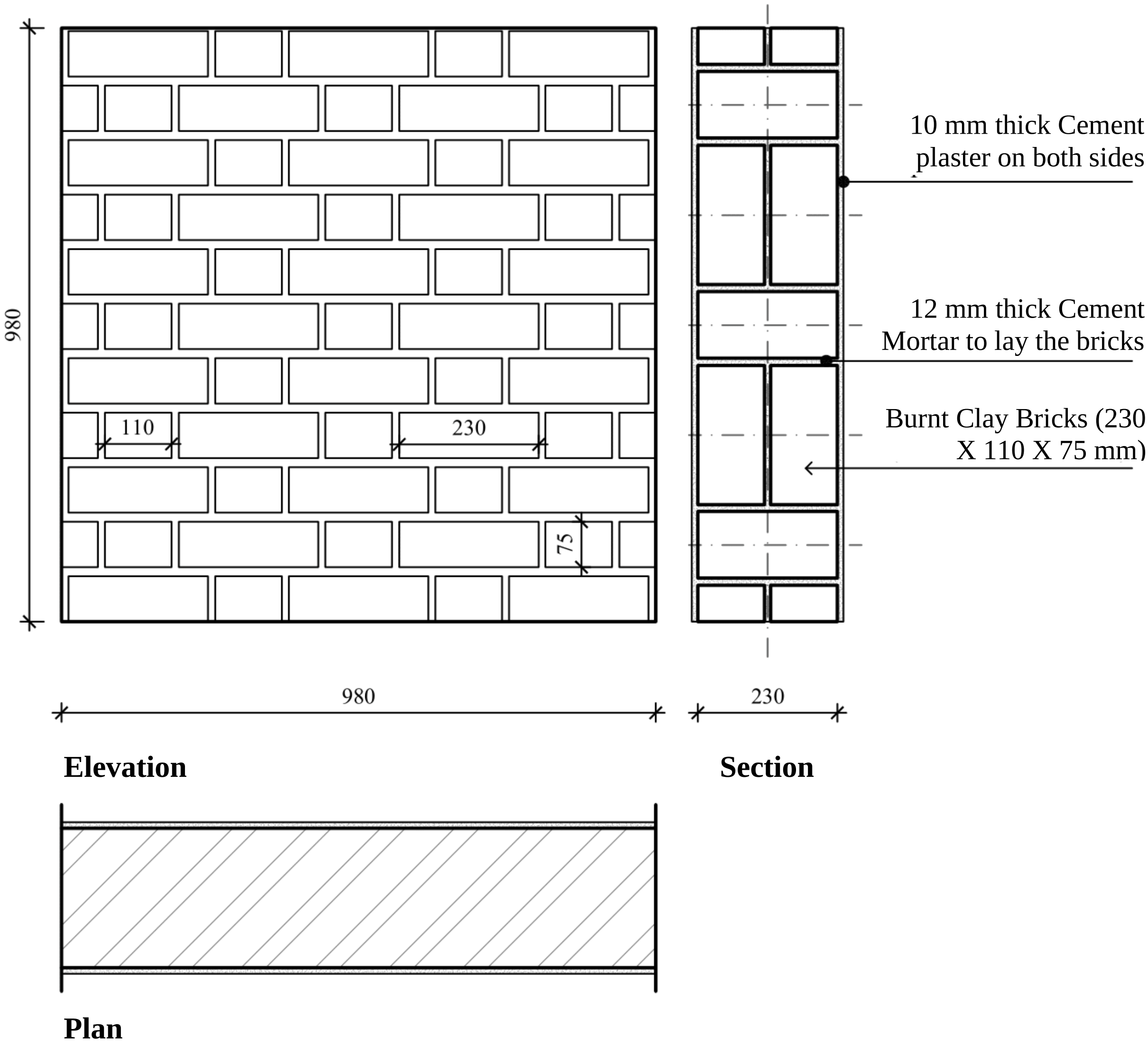


Figure 90: Schematic drawings of burnt clay brick wall sample

Table 12: Walling technology and testing details for burnt clay brick wall sample

Particulars	Dimensions	Specification	Properties		Testing Method	
			Conductivity	Specific heat	Particulars	Total Wall assembly
Cement Plaster coat (for both sides)	10 mm thick (cement : sand in 1:1 ratio)	IS 1661:1972				
Cement Mortar Mix	12 mm thick (cement:sand in 1:1 ratio)	IS 2250:1981				ASTM C 1363
Burnt Clay Bricks	230 X 110 X 75 mm	IS 1077:1991				

6. Structural Stay-in-Place formwork system

Total wall thickness= 230 mm

U value of the assembly= 0.44 W/m^2K

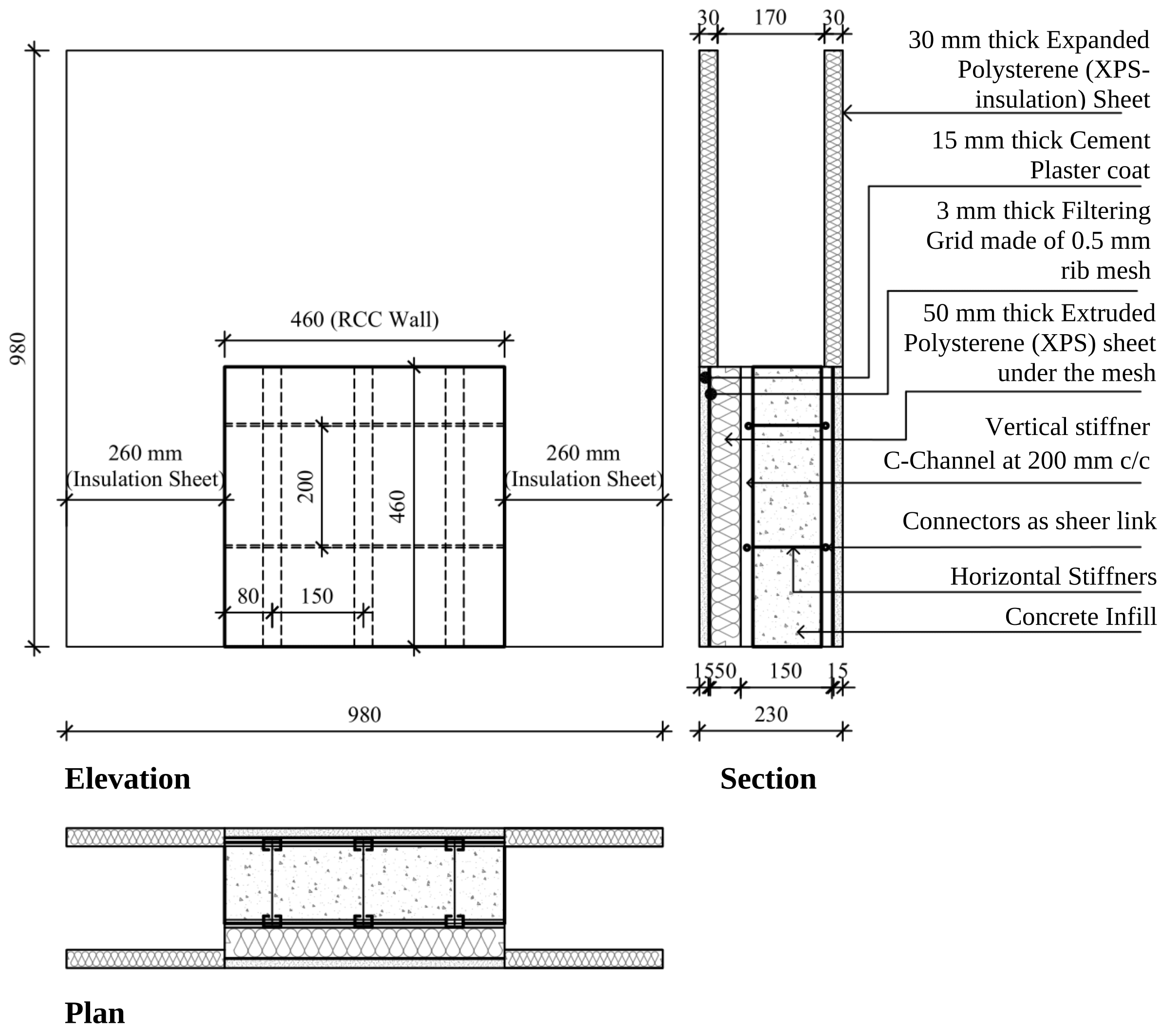


Figure 91 : Schematic drawing of Structural Stay-in-Place Formwork (Coffor) wall sample with insulation as per specifications found in BMTPC Performance Appraisal Certificate (PAC) no: 1035-S/ 2018.

Table 13 : Walling technology and testing details for of Structural Stay-in-Place Formwork (Coffor) wall sample with insulation

Particulars	Dimensions	Specification	Properties		Testing Method	
			Conductivity	Specific heat	Particulars	Total Wall assembly
Extruded Polysterene (EPS) Sheet	30 mm thick	ASTM C578-19				ASTM C 1363
Cement Plaster (for both sides)	15 mm thick	IS 1661:1972				
Filtering Grid on both sides	3 mm thick (with a grid made of 0.5 mm rib mesh)					
Extruded polyseteren (XPS) sheet attached to the filtering grid	50 mm thick	ASTM C578-19				
Concete (infill) mix with the steel reinforcement	150 mm thick	IS 456:2000				

7. Bamboo Crete Wall

Total wall thickness= 65mm

U value of the assembly= 2.71 W/m^2K

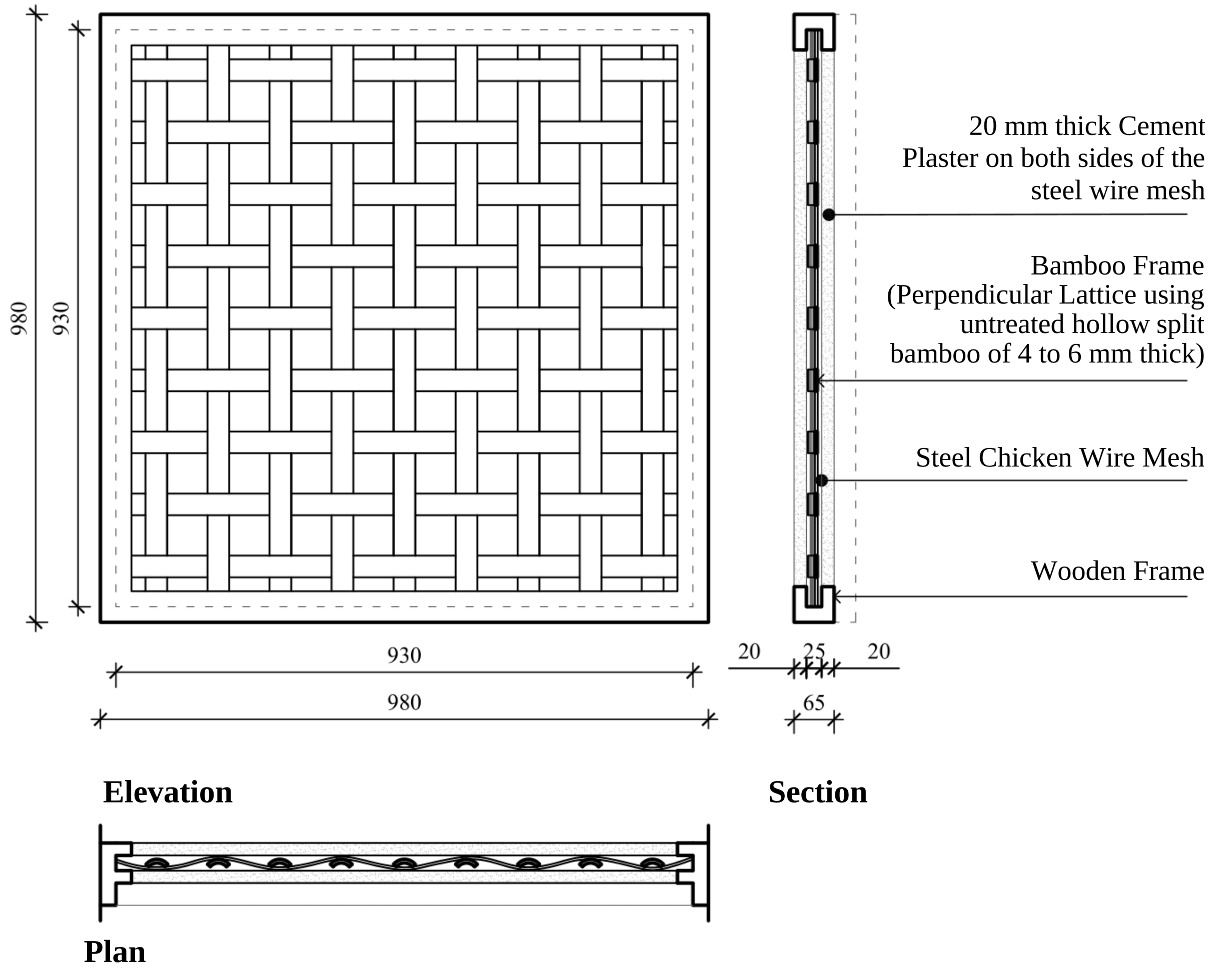


Figure 92 : Schematic plan and elevation of the Bamboo-Crete Wall

Table 14 : Walling technology and testing details for Bamboo-Crete Wall

Particulars	Dimensions	Specification	Properties: Conductivity	Properties: Specific heat	Testing Method: Particulars	Testing Method: Total Wall assembly
Cement Plaster Mix (for both sides)	20 mm thick (cement:sand in 1:6 ratio)	IS 1661:1972	1.335 W/m.K	916.87 J/kg K 0.8727 MJ/m^3K	ISO 22007-2	
Steel Chicken Wire Mesh on both sides	2-3 mm thick	IS:3150-1982				ASTM C 1363
Bamboo Frame (Perpendicular Lattice using untreated hollow split bamboo)	25 mm thick					

8. Wattle and Daub Wall

Total wall thickness= 45 mm

U value of the assembly= 3.61 W/m^{2}K

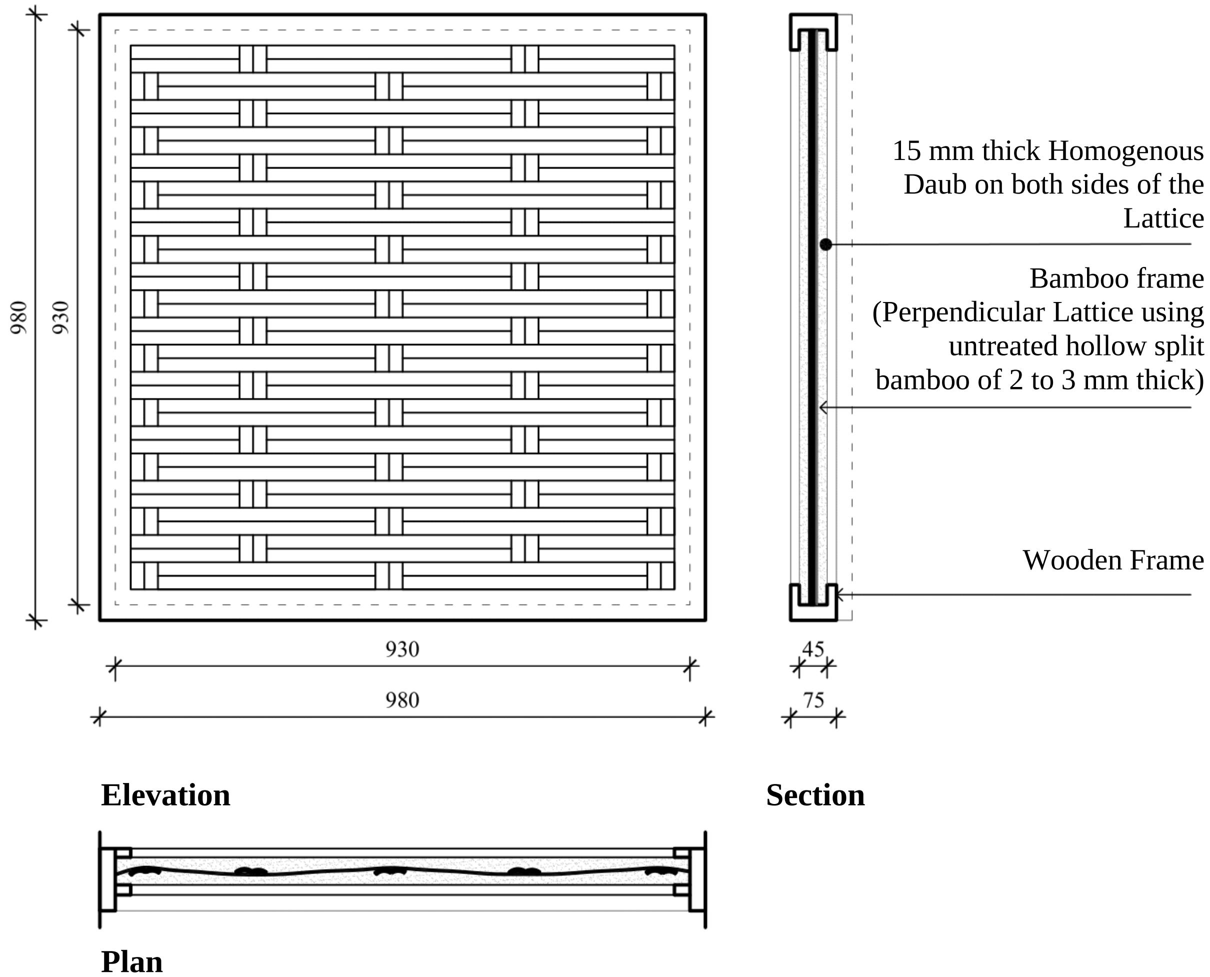


Figure 93: Schematic drawings of the Wattle and Daub Wall

Table 15 : Walling technology and testing details for Wattle and Daub Wall

Particulars	Dimensions	Specification	Properties		Testing Method	
			Conductivity	Specific heat	Particulars	Total Wall assembly
Homogenous Daub mix (for both sides of the bamboo lattice frame)	15 mm thick (Red Soil: Cowdung: Grass husk/Jute fibres:Water in 16:4:4:3 ratio)					ASTM C 1363
Bamboo Frame	45 mm thick width of the total frame (Perpendicular Lattice using 2-3 mm thick untreated hollow split bamboo)					

9. Stabilized Adobe Wall

Total wall thickness= 230 mm

U value of the assembly= 2.11 W/m^{2}K

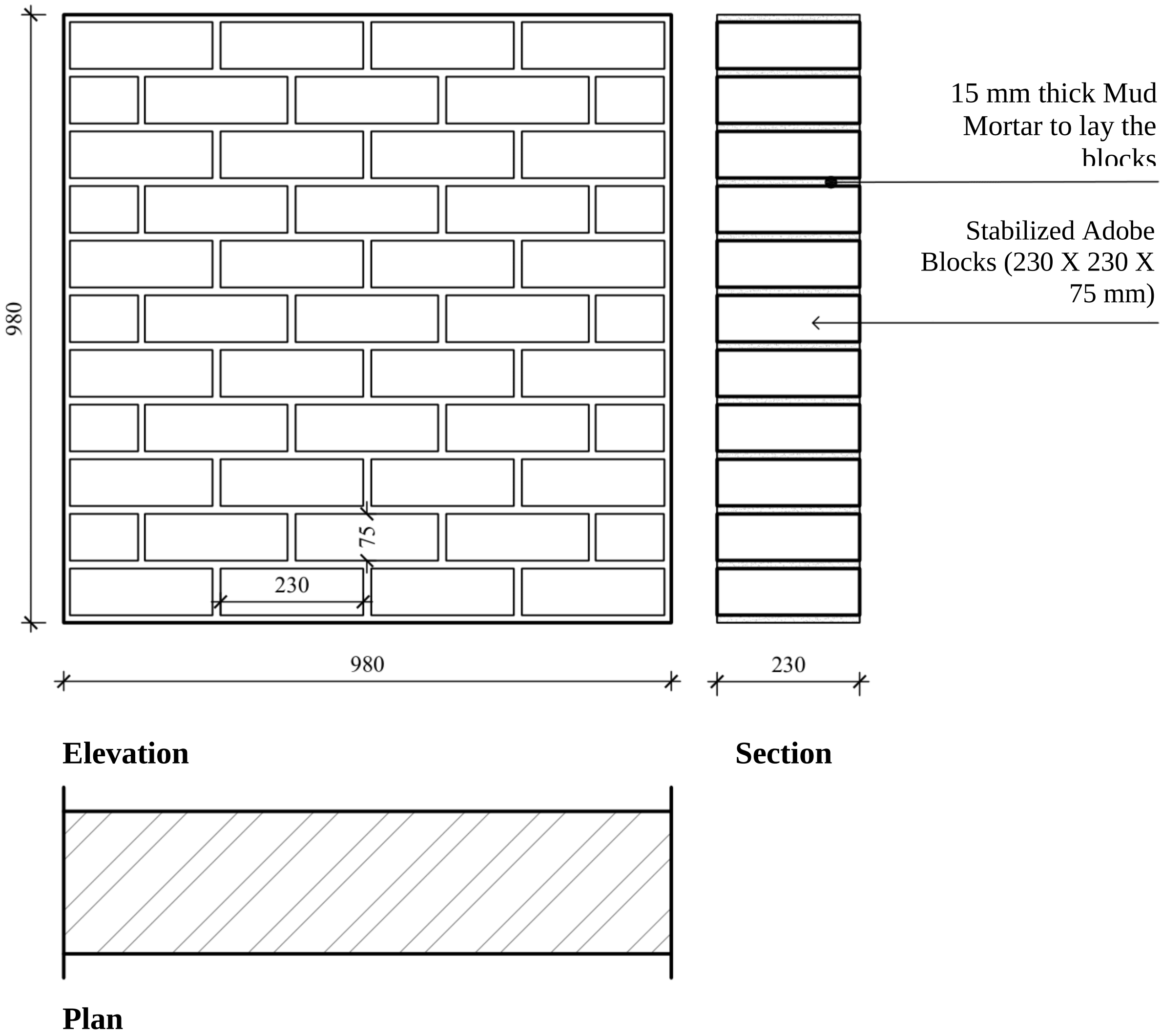


Figure 94 : Schematic drawings of the Stabilized Adobe Wall

Table 16 : Walling technology and testing details for Stabilized Adobe Wall

Particulars	Dimensions	Specification	Properties		Testing Method	
			Conductivity	Specific heat	Particulars	Total Wall assembly
Mud Mortar mix	15 mm thick (sand:soil in 1:5 ratio)	IS 13077:1991				ASTM C 1363
Stabilized Adobe Blocks	230 x 230 x 75 mm (soil:sand :cement:husk in 9:3:0.5:4.5 ratio)	IS 1725:1982				

10. Laterite Block Wall

Total wall thickness= 230 mm

U value of the assembly= 2.17 W/m^{2}K

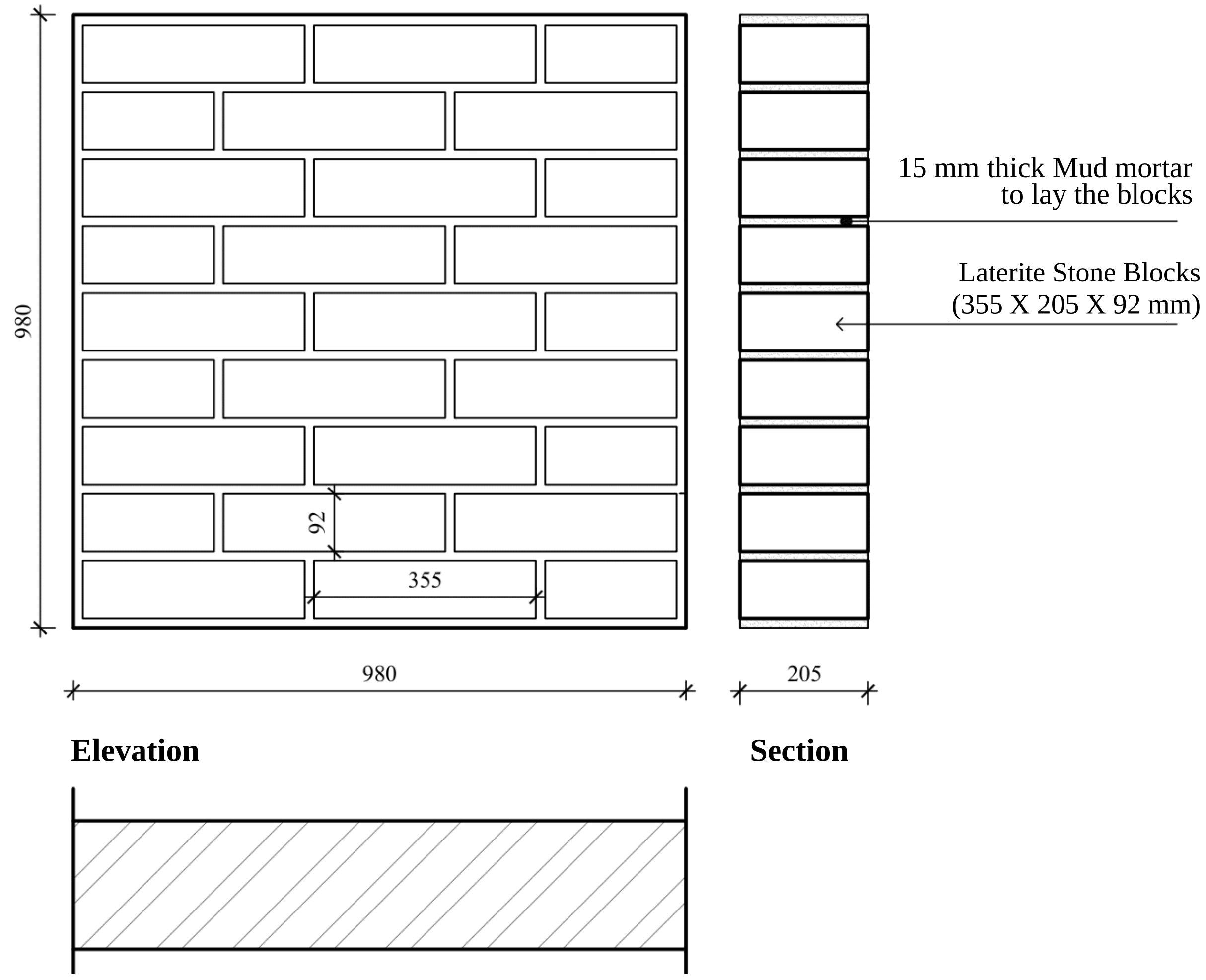


Figure 95 : Schematic drawings of the Laterite Block Wall

Table 17 : Walling technology and testing details for Laterite Block Wall

Particulars	Dimensions	Specification	Properties		Testing Method	
			Conductivity	Specific heat	Particulars	Total Wall assembly
Mud Mortar mix	15 mm thick (sand:soil in 1:5 ratio)	IS 13077:1991				ASTM C 1363
Laterite Blocks	355 x 205 x 92 mm					

11. Unstabilized Adobe Wall

Total wall thickness= 230 mm

U value of the assembly= 2.05 W/m^{2}K

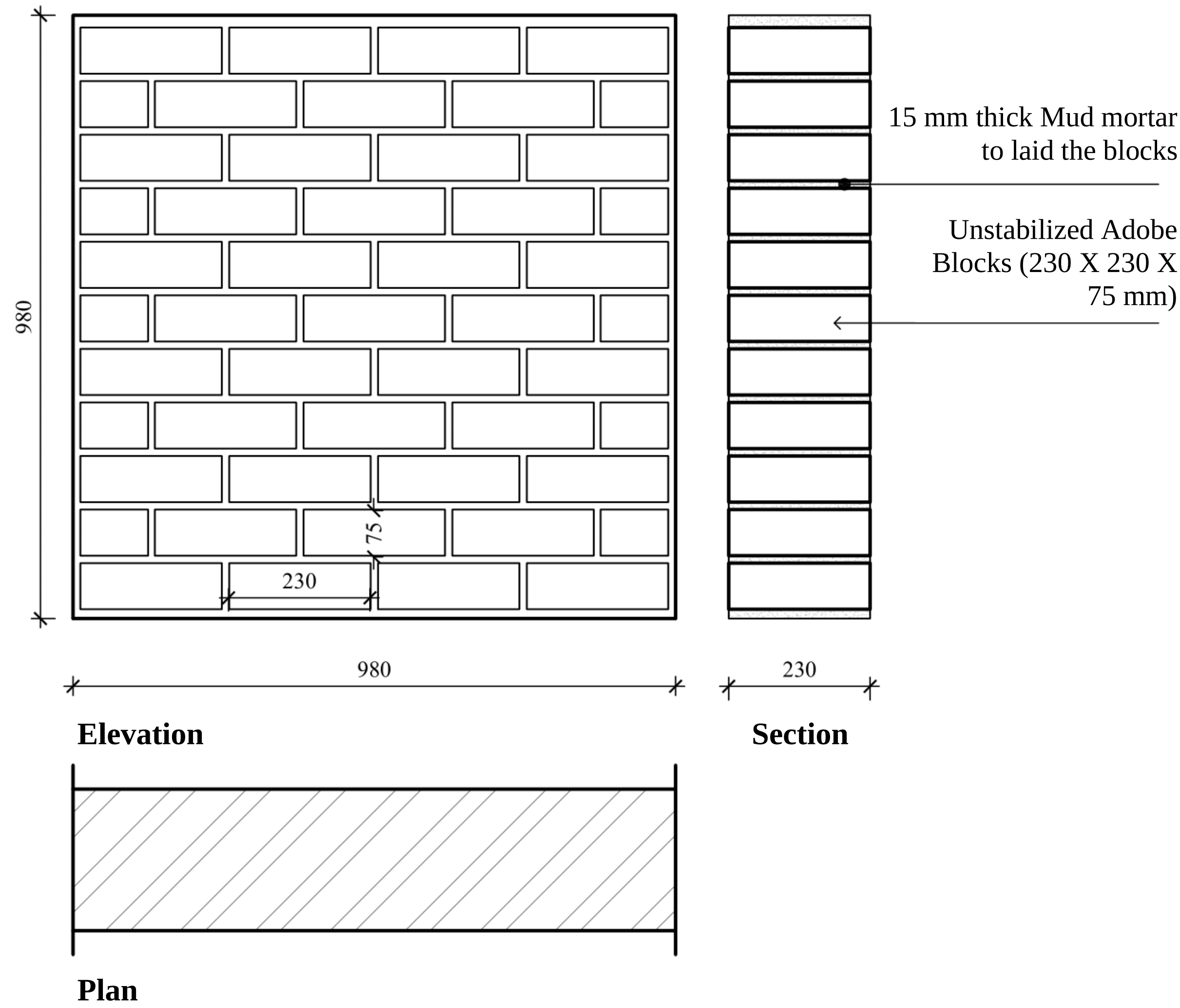


Figure 96 : Schematic drawings of the Unstabilized Adobe Wall

Table 18: Walling technology and testing details for Unstabilized Adobe Wall

Particulars	Dimensions	Specification	Properties		Testing Method	
			Conductivity	Specific heat	Particulars	Total Wall assembly
Mud Mortar mix	15 mm thick (sand:soil in 1:5 ratio)	IS 13077:1991				ASTM C 1363
Unstabilized Adobe Blocks	230 x 230 x 75 mm (soil:sand: cement husk in 9:3:0.5:4.5 ratio)	IS 1725:1982				

12. Compressed Stabilized Earth Block (CSEB) Wall

Total wall thickness= 230 mm

U value of the assembly= 2.79 W/m^{2}K

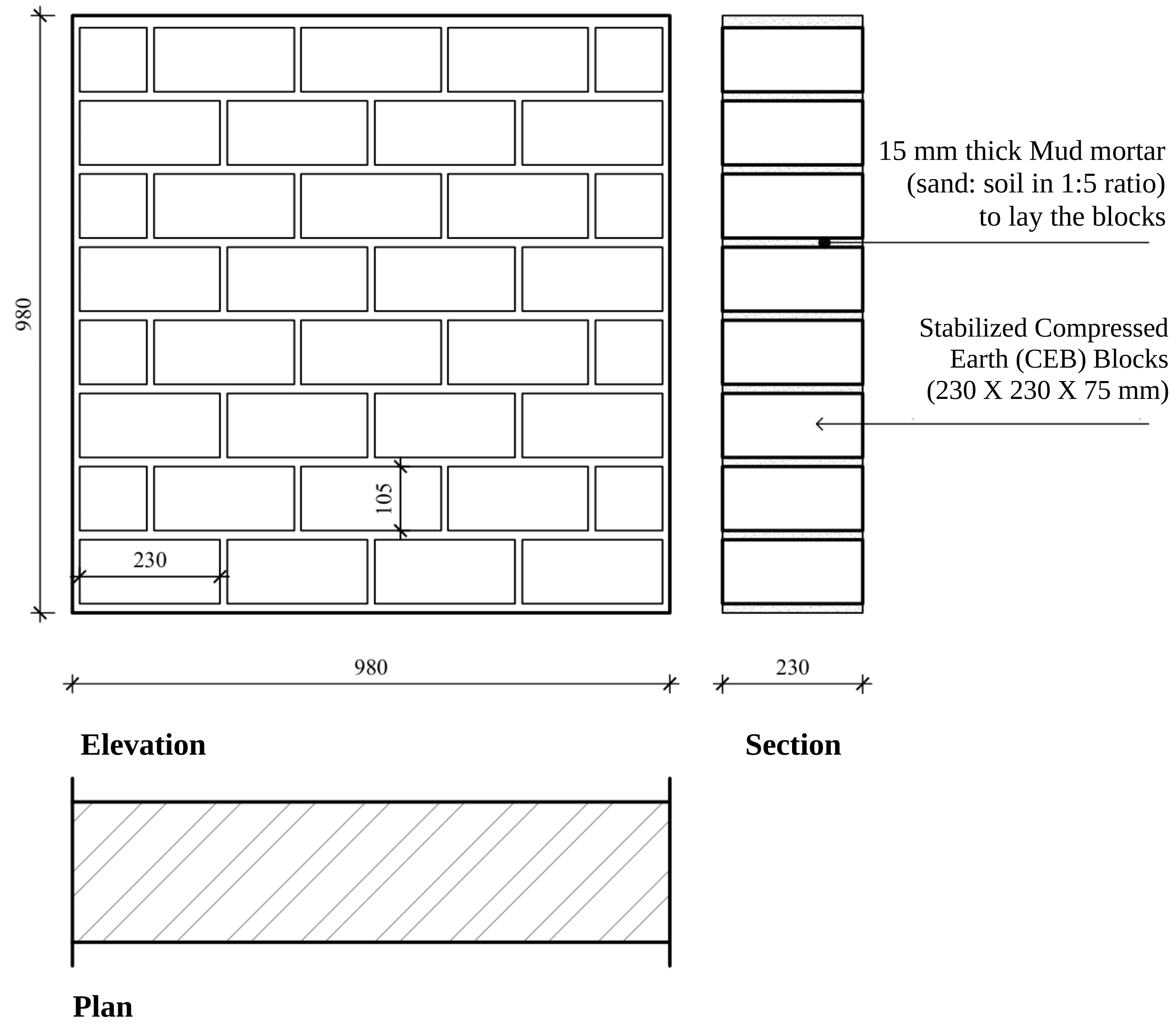


Figure 97: Schematic drawings of the Compressed Stabilized Earth Block (CSEB) Wall

Table 19: Walling technology and testing details for Compressed Stabilized Earth Block (CSEB) Wall

Particulars	Dimensions	Specification	Properties		Testing Method	
			Conductivity	Specific heat	Particulars	Total Wall assembly
Mud Mortar mix	15 mm thick (sand:soil in 1:5 ratio)	IS 13077:1991				ASTM C 1363
Stabilized Compressed Earth Blocks (CEB)	230 x 230 x 75 mm (soil:sand :cement:husk in 9:3:0.5:4.5 ratio)	IS 1725:1982				

13. Unstabilized Compressed Earth Block (CEB) Wall

Total wall thickness= 230 mm

U value of the assembly= 2.74 W/m^{2}K

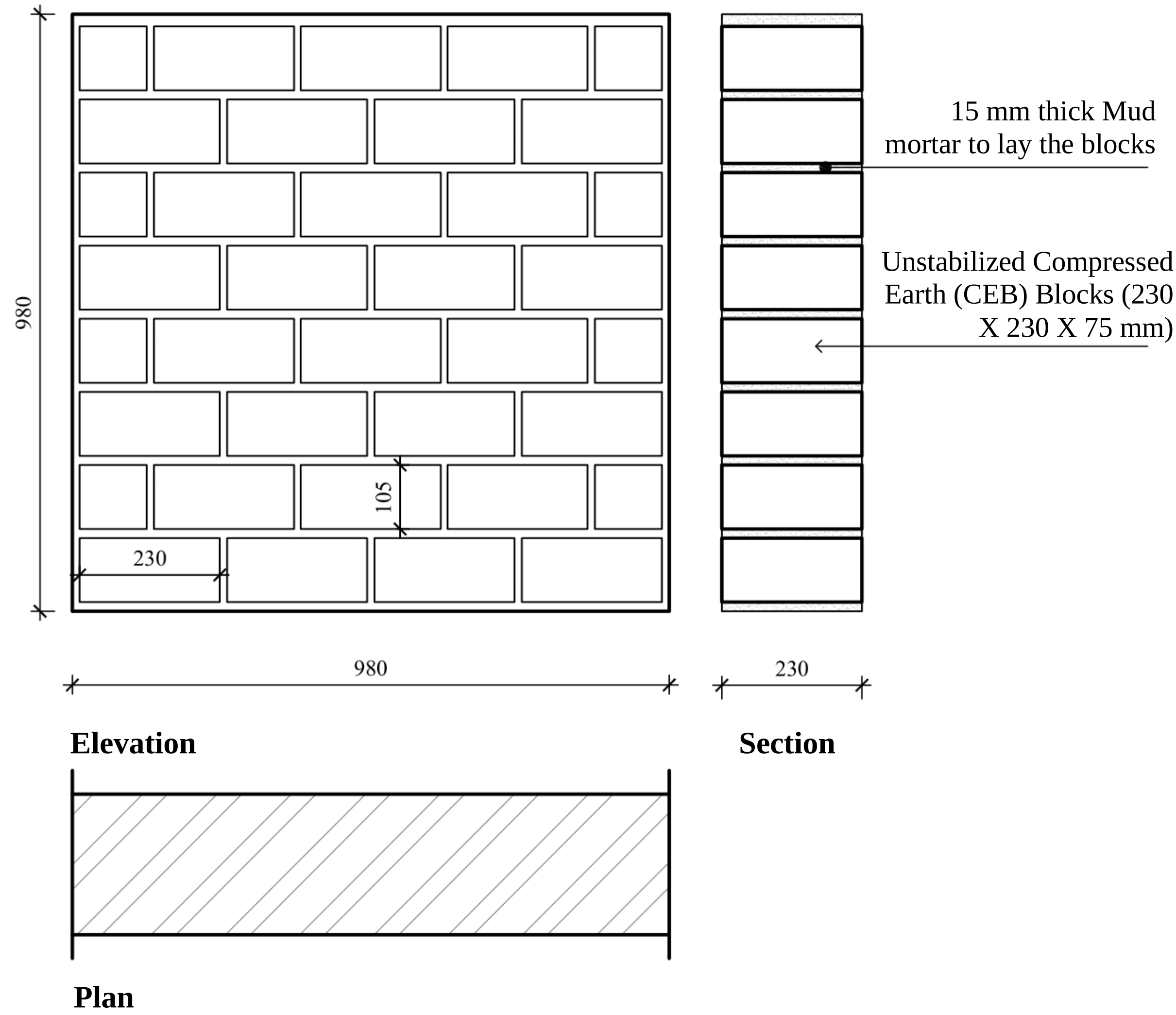


Figure 98 : Schematic drawings of the Unstabilized Compressed Earth Block (CEB) Wall

Table 20: Walling technology and testing details for Unstabilized Compressed Earth Block Wall

Particulars	Dimensions	Specification	Properties		Testing Method	
			Conductivity	Specific heat	Particulars	Total Wall assembly
Mud Mortar mix	15 mm thick (sand:soil in 1:5 ratio)	IS 13077:1991				ASTM C 1363
Unstabilized Compressed Earth Blocks (CEB)	230 x 230 x 75 mm (soil:sand :cement:husk in 9:3:0.5:4.5 ratio)	IS 1725:1982				

14. Autoclaved Aerated Concrete (AAC) Block Wall with Perlite-based Cement Plaster

Total wall thickness= 230 mm

U value of the assembly= 0.76 W/m^2K

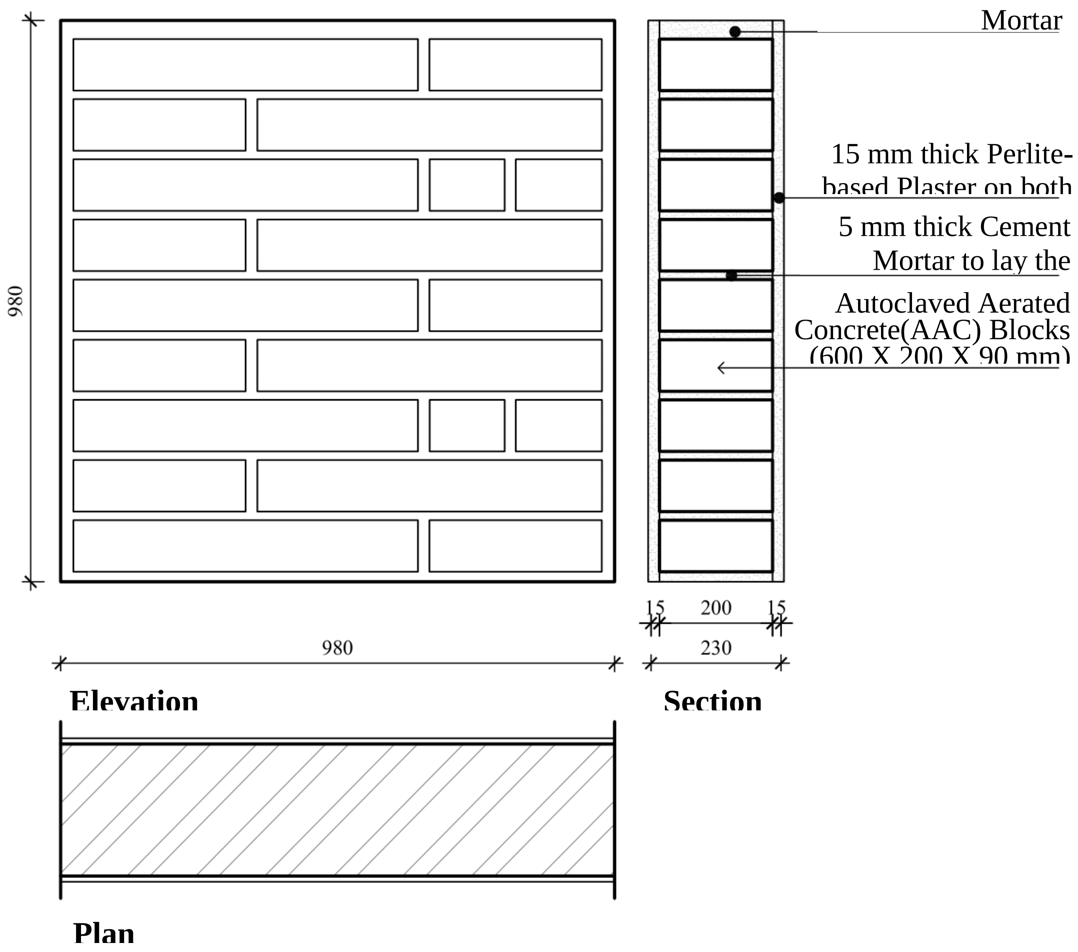


Figure 99: Schematic drawings of the Autoclave Aerated Concrete Block Wall with Perlite-based cement plaster

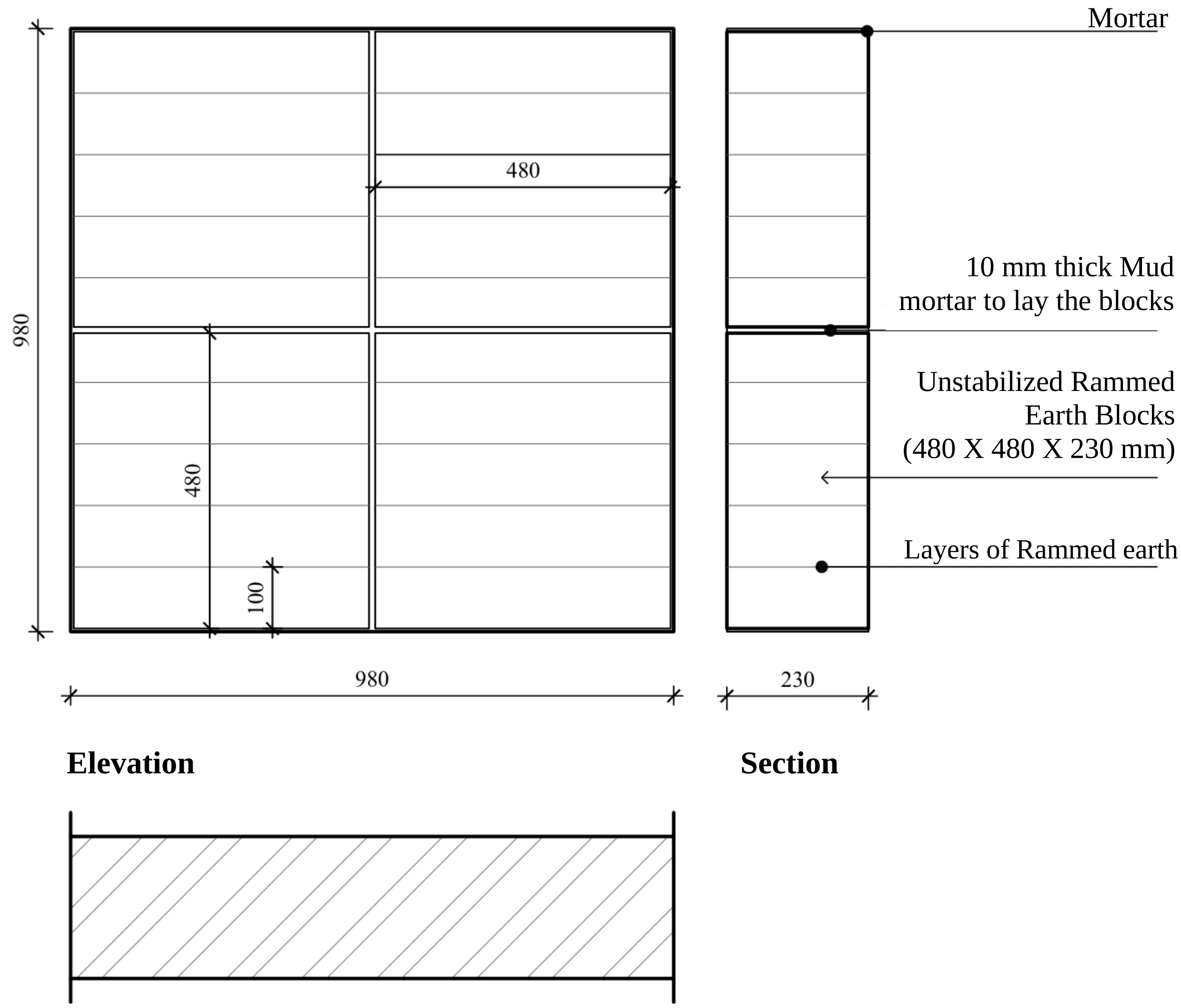
Table 21:Walling technology and testing details for AAC Block Wall with Perlite-based cement plaster

Particulars	Dimensions	Specification	Properties		Testing Method	
			Conductivity	Specific heat	Particulars	Total Wall assembly
Perlite-based Plaster (for both sides)	15 mm thick		0.1144 W/m.K	0.01017 MJ/m^3K		
Cement Mortar mix	5 mm thick	IS 2250:1981	1.487 W/m.K	942.16 J/Kg.K	ISO 22007-2	ASTM C 1363
Autoclave Aerated Concrete (AAC) Block	600 X 200 X 90 mm	IS: 2185 (Part 3)-1984	0.1877 W/m.K	0.6269 MJ/m^3K or 924.15 J/Kg.K		

15. Unstabilized Rammed Earth Wall

Total wall thickness= 230 mm

U value of the assembly= 2.13 W/m^{2}K



Plan

Figure 100 : Schematic drawings of the Unstabilized Rammed Earth Wall

Table 22 : Walling technology and testing details for Unstabilized Rammed Earth Wall

Particulars	Dimensions	Specification	Properties		Testing Method	
			Conductivity	Specific heat	Particulars	Total Wall assembly
Mud Mortar mix	10 mm thick (sand:soil in 1:5 ratio)	IS 13077:1991				
Rammed Earth Block (Unstabilized)	480 X 480 X 230 mm (sand, soil, and aggregate in the 2:6:4 ratio for the dry mixture)	ASTM E2392/ E2392M: 2016				ASTM C 1363

16. Stabilized Rammed Earth Wall

Total wall thickness= 230 mm

U value of the assembly= 2.09 W/m^2K

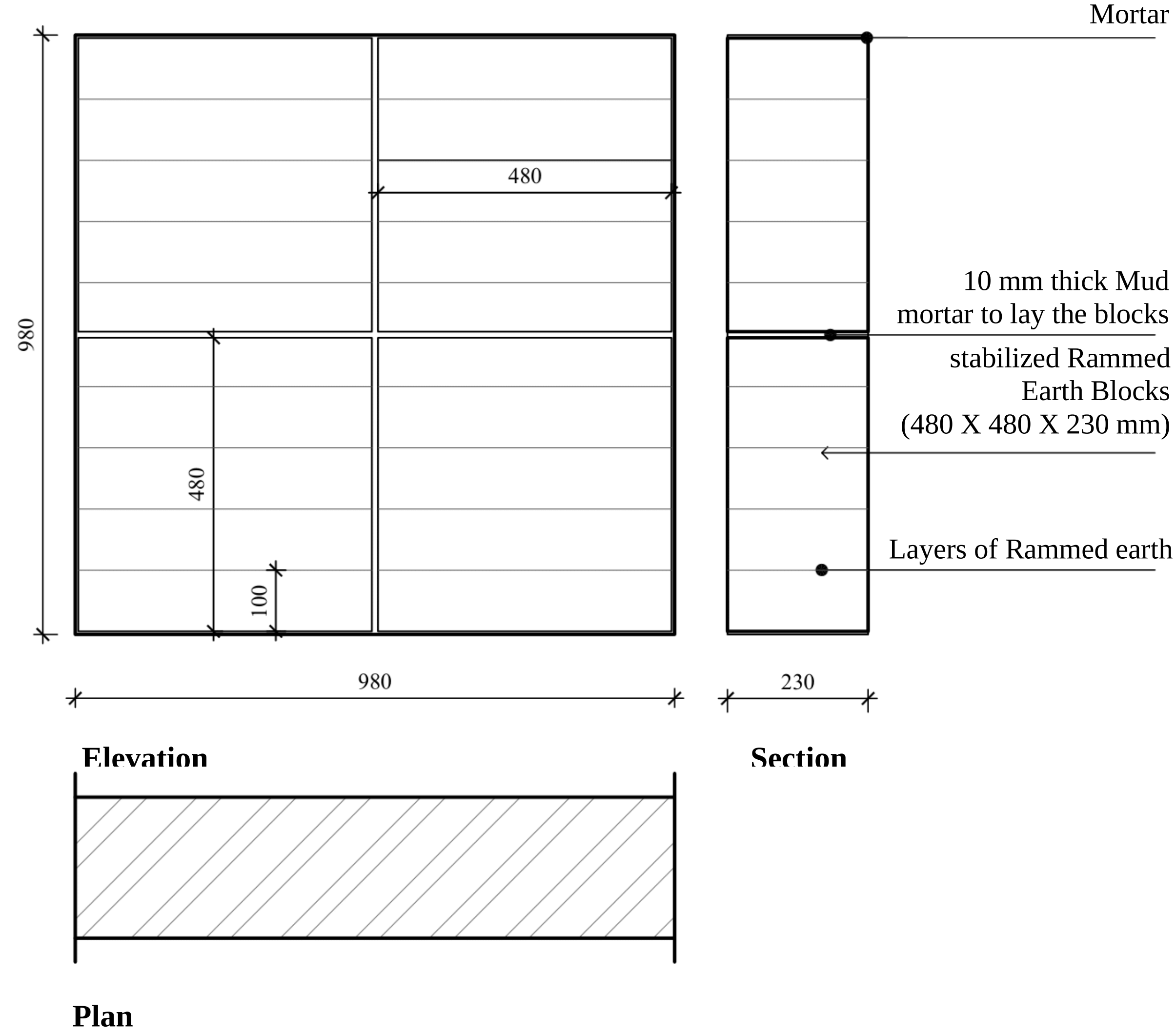


Figure 101 : Schematic drawings of the Stabilized Rammed Earth Wall

Table 23 : Walling technology and testing details for Stabilized Rammed Earth Wall

Particulars	Dimensions	Specification	Properties		Testing Method	
			Conductivity	Specific heat	Particulars	Total Wall assembly
Mud Mortar mix	10 mm thick (sand:soil in 1:5 ratio)	IS 13077:1991				ASTM C 1363
Rammed Earth Block (Stabilized)	480 X 480 X 230 mm (sand, soil, and aggregate in the 2:6:4 ratio for the dry mixture)	ASTM E2392/ E2392M: 2016	0.5755 W/m.K	1.208 MJ/m^3K	ISO 22007-2	

17. AAC Block Wall with Cement Mortar and Cement Plaster

Total wall thickness= 230 mm
U value of the assembly= 0.78 W/m^{2}K

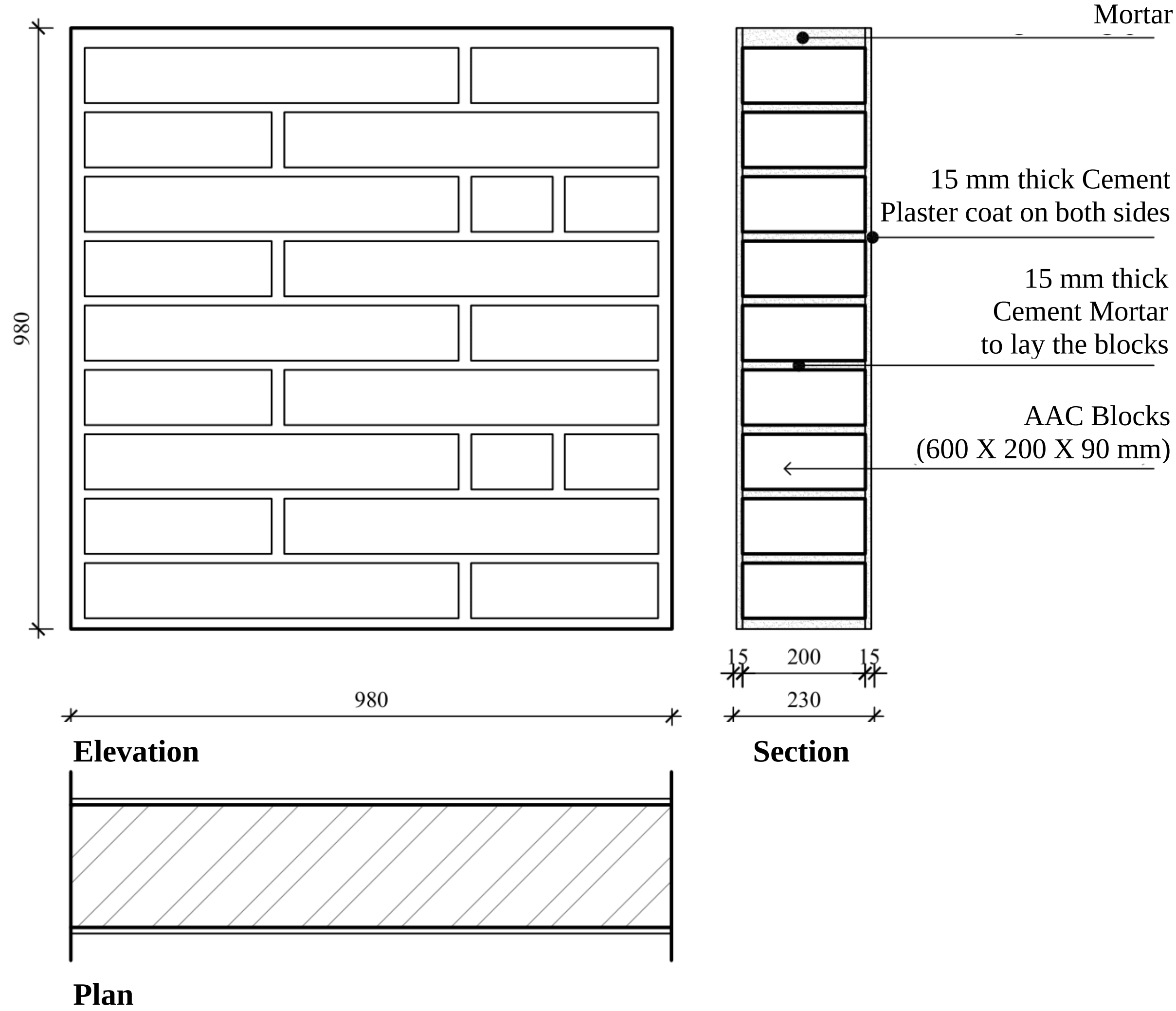


Figure 102: Schematic drawings of AAC block wall with cement mortar and cement plaster

Table 24: Walling technology and testing details for AAC block wall with cement mortar and plaster

Particulars	Dimensions	Specification	Properties: Conductivity	Properties: Specific heat	Testing Method: Particulars	Testing Method: Total Wall assembly
Cement Plaster mix (for both sides)	15 mm thick	IS 1661:1972	1.411 W/m.K	916.07 J/kg.K or 1.050 MJ/m^{3}K		
Cement Mortar mix	15 mm thick (cement:sand in 1:4 ratio)	IS: 2250-1981	1.393 W/m.K	942.28 J/kg.K or 0.8308 MJ/m^{3}K	ISO 22007-2	ASTM C 1363
Autoclave Aerated Concrete (AAC) Block	600 X 200 X 90 mm	IS: 2185 (Part 3)-1984	0.1810 W/m.K	893.77 J/kg.K or 0.5111 MJ/m^{3}K		

18. AAC Block Wall with Lime Mortar and Cement Plaster

Total wall thickness= 220 mm
U value of the assembly= 0.82 W/m^{2}K

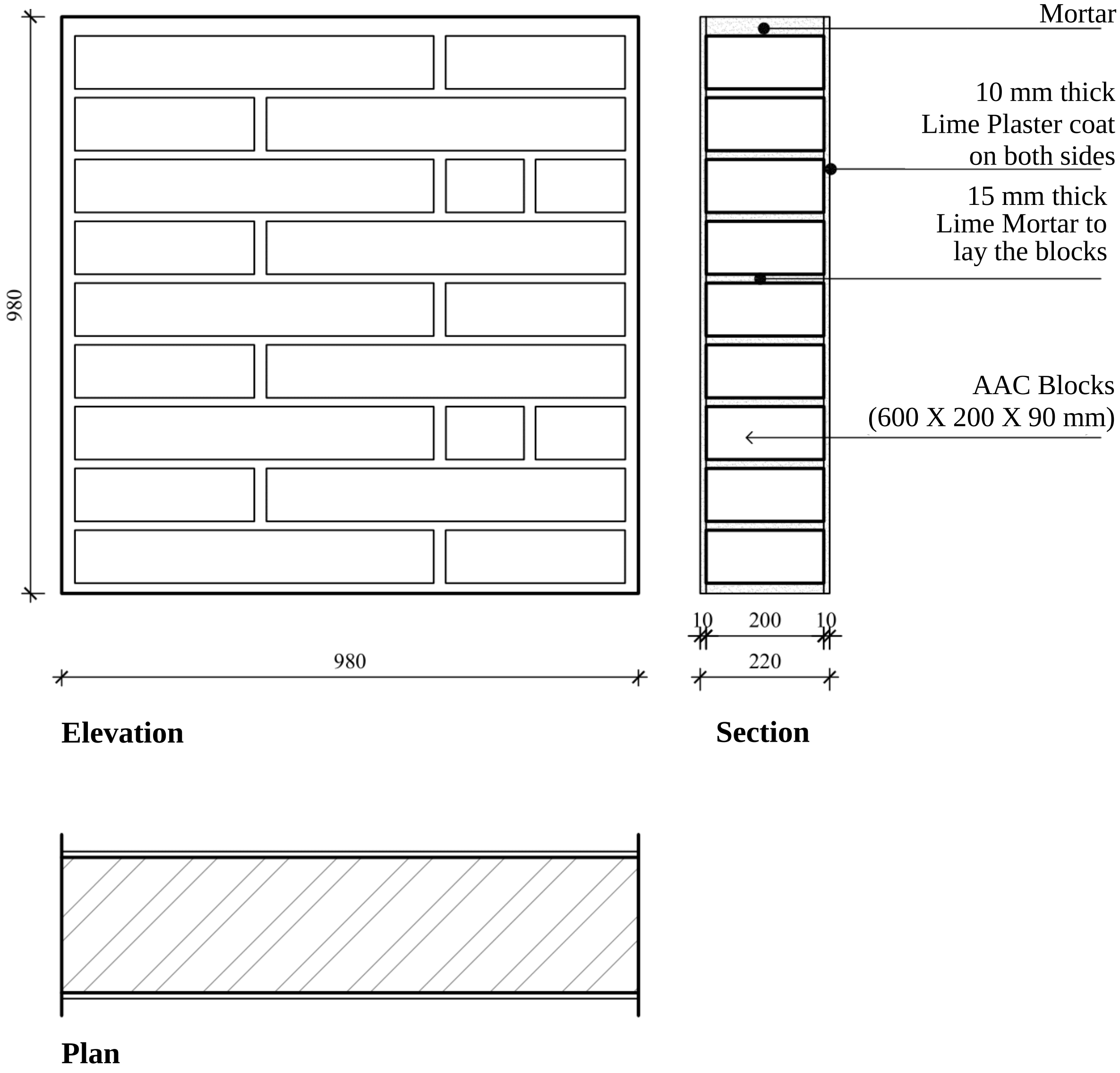


Figure 103 : Schematic drawings of AAC block wall with lime mortar and lime plaster

Table 25: Walling technology and testing details for AAC block wall with lime mortar and lime plaster

Particulars	Dimensions	Specification	Properties		Testing Method	
			Conductivity	Specific heat	Particulars	Total Wall assembly
Lime Plaster mix (for both sides)	10 mm thick (lime: sand in 1:4 ratio)	IS: 2394-1984	0.946 W/m.K	850.73 J/kg.K 1.699 MJ/m³K	ISO 22007-2	ASTM C 1363
Lime Mortar mix	15 mm thick (lime: sand in 1:3 ratio)	IS: 712-1984	0.847 W/m.K	834.60 J/kg.K 1.630 MJ/m³K		
Autoclave Aerated Concrete (AAC) Block	600 X 200 X 90 mm	IS: 2185 (Part 3)-1984	0.181 W/m.K	893.77 J/kg.K 0.511 MJ/m³K		

19. Burnt Clay Brick Wall with Lime Mortar and Lime Plaster

Total wall thickness= 250 mm

U value of the assembly= 2.31 W/m^{2}K

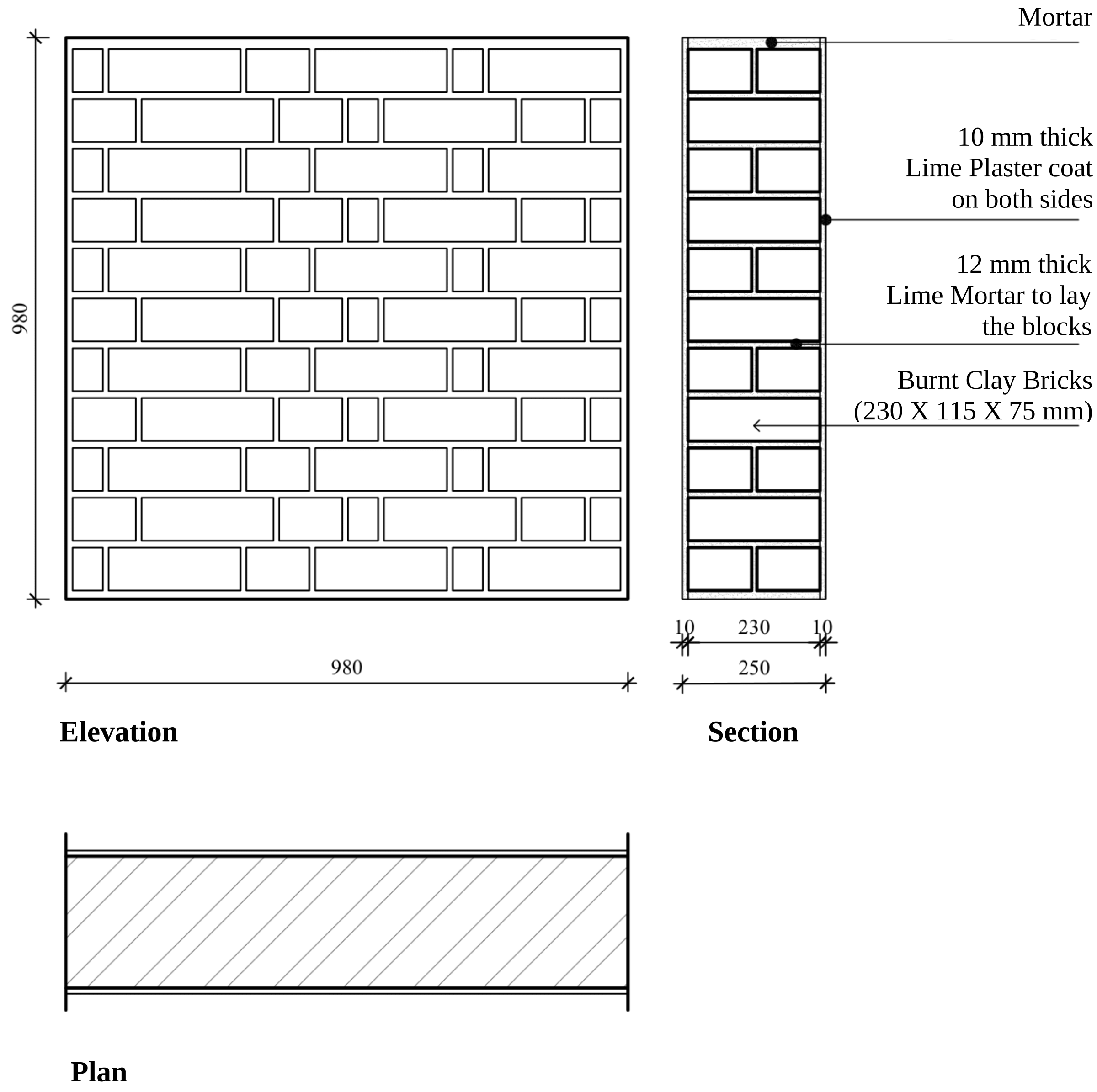


Figure 104: Schematic Illustration of burnt clay brick wall with lime mortar and lime plaster

Table 26: Walling technology and testing details for burnt clay brick wall with lime mortar and lime plaster

Particulars	Dimensions	Specification	Properties		Testing Method	
			Conductivity	Specific heat	Particulars	Total Wall assembly
Lime Plaster mix (for both sides)	10 mm thick (lime: sand in 1:4 ratio)	IS: 2394-1984	1.003 W/m.K	814.26 J/kg.K 1.822 MJ/m^3K	ISO 22007-2	ASTM C 1363
Lime Mortar mix	12 mm thick (lime: sand in 1:3 ratio)	IS: 712-1984	0.9617 W/m.K	856.28 J/kg.K 1.688 MJ/m^3K		
Brunt Clay Brick	230 X 115 X 75 mm	IS 1077:1992	0.5069 W/m.K	933.31 J/kg.K 0.7963 MJ/m^3K		

20. Limestone with Lime Mortar and Lime Plaster

Total wall thickness= 250 mm
U value of the assembly= 2.84 W/m²K

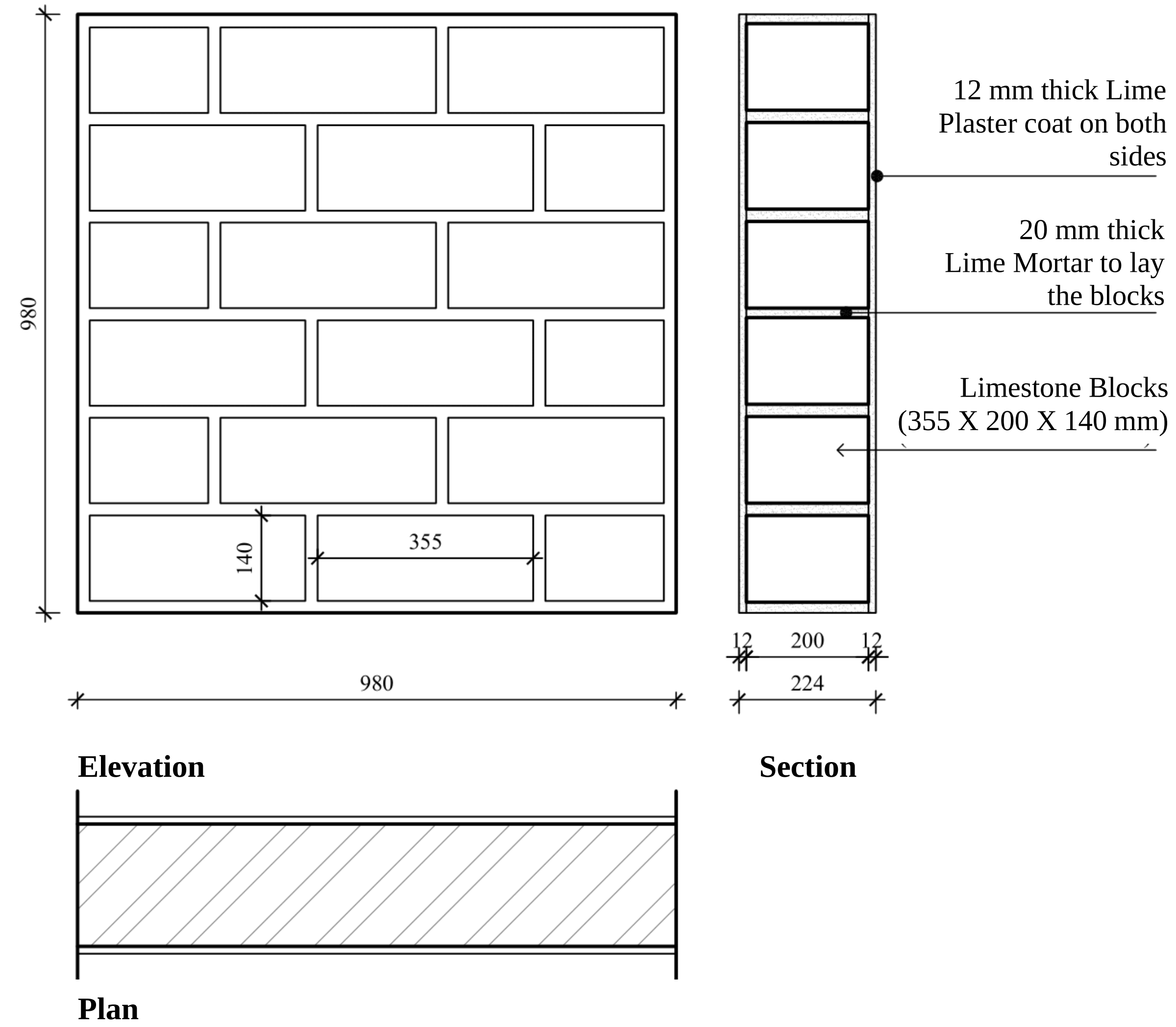


Figure 105: Schematic drawings of Limestone wall with lime mortar and lime plaster

Table 27 : Walling technology and testing details for Limestone wall with lime mortar and lime plaster

Particulars	Dimensions	Specification	Properties: Conductivity	Properties: Specific heat	Testing Method: Particulars	Testing Method: Total Wall assembly
Lime Plaster mix on both sides	12 mm thick (lime: sand in 1:4 ratio)	IS: 2394-1984	0.9461 W/m.K	804.06 J/kg.K 1.474 MJ/m³K	ISO 22007-2	ASTM C 1363
Lime Mortar mix	20 mm thick (lime: sand in 1:3 ratio)	IS: 712-1984	0.8626 W/m.K	834.57 J/kg.K 1.290 MJ/m³K		
Limestone Block	355 X 200 X 140 mm	IS: 2185 (Part 3)-1984	0.9694 W/m.K			

21. Limestone Wall with Cement Mortar and Cement Plaster

Total wall thickness= 250 mm

U value of the assembly= 2.82 W/m^{2}K

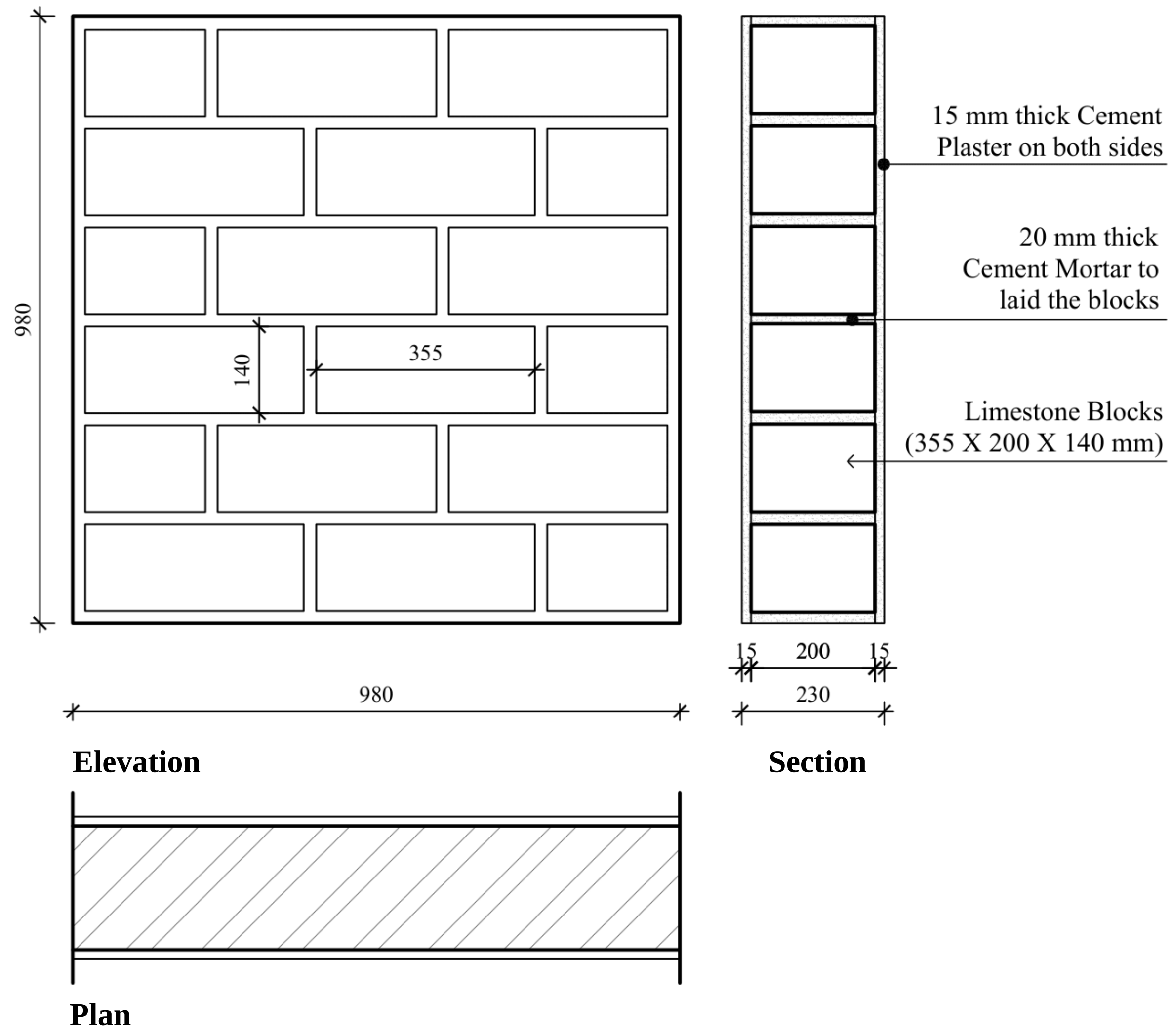


Figure 106: Schematic drawings of Limestone wall with cement mortar and cement plaster

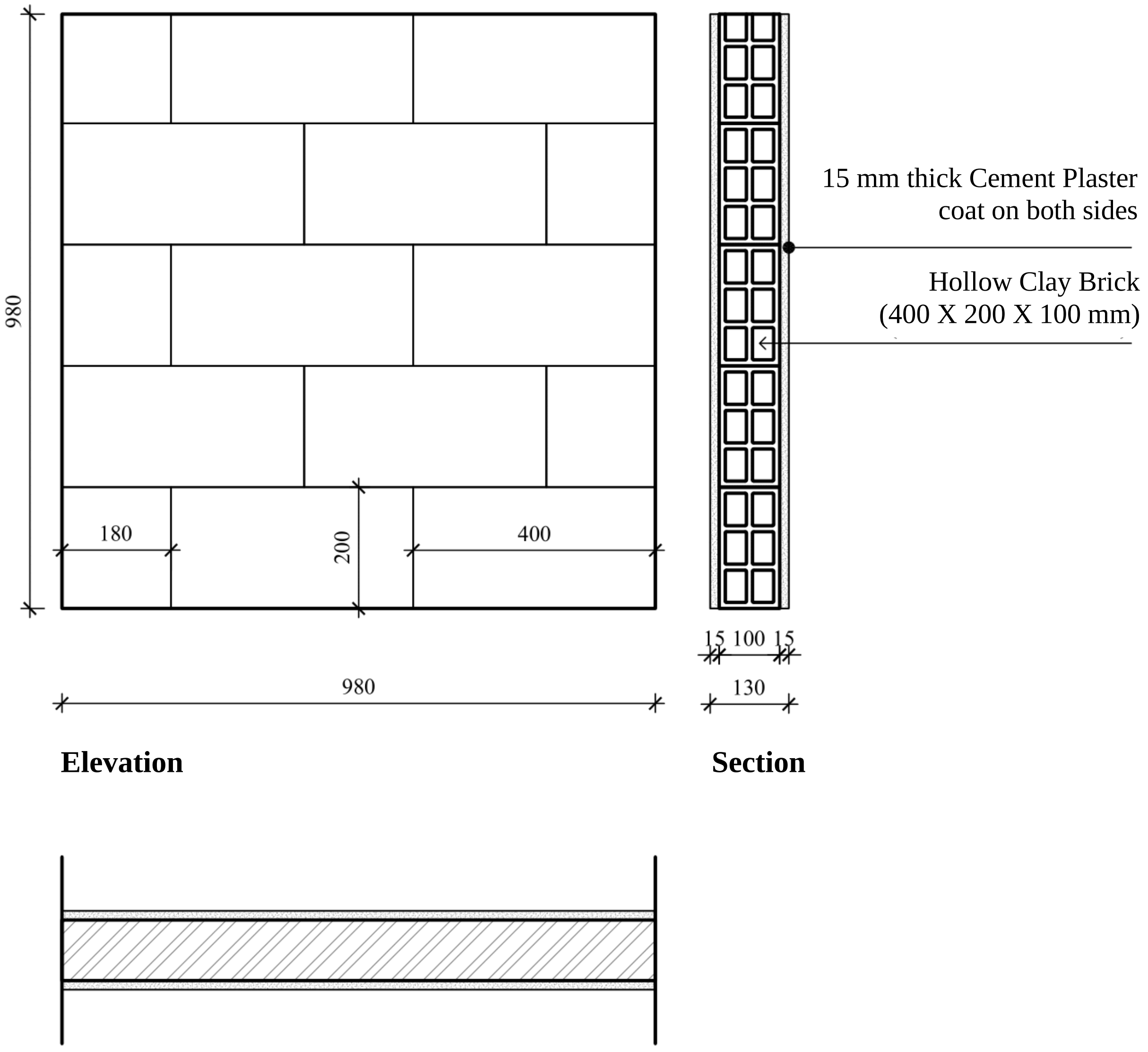
Table 28: Walling technology and testing details for Limestone wall with cement mortar and plaster

Particulars	Dimensions	Specification	Properties		Testing Method	
			Conductivity	Specific heat	Particulars	Total Wall assembly
Cement Plaster mix (for both sides)	15 mm thick (cement: sand in 1:4 ratio)	IS 1661:1972	1.205 W/m.K	927.89 J/kg.K 1.315 MJ/m^{3}K	ISO 22007-2	ASTM C 1363
Cement Mortar mix	20 mm thick (cement: sand in 1:4 ratio)	IS: 2250-1981	1.386 W/m.K	866.99 J/kg.K 1.113 MJ/m^{3}K		
Limestone Block	355 X 200 X 140 mm	IS: 2185 (Part 3)-1984	0.9694 W/m.K			

22. Hollow Clay Brick (100 mm thk) Wall with Cement Plaster

Total wall thickness= 130 mm

U value of the assembly= 2.71 W/m^{2}K



Plan

Figure 107: Schematic drawings of hollow clay (100 mm)brick with cement plaster coat on both sides

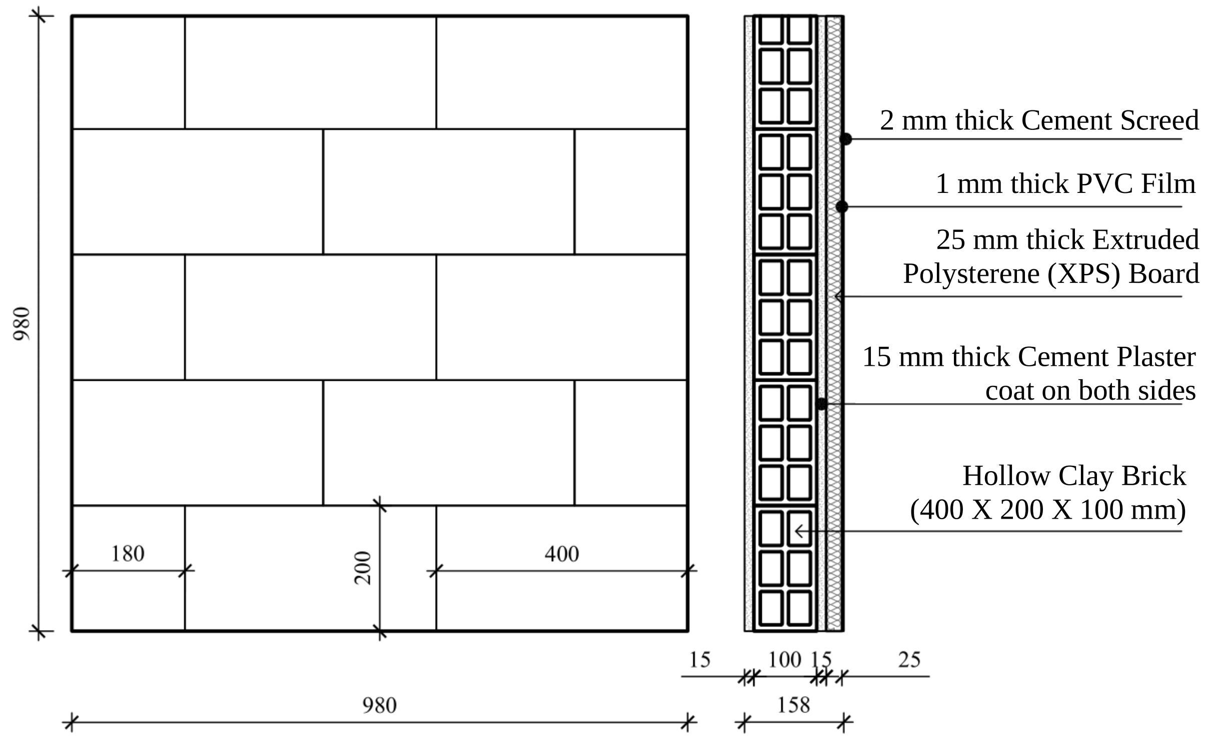
Table 29: Walling technology and testing details for hollow clay (100 mm)brick with cement plaster

Particulars	Dimensions	Specification	Properties		Testing Method	
			Conductivity	Specific heat	Particulars	Total Wall assembly
Cement Plaster mix (for both sides)	15 mm thick (cement: sand in 1:1 ratio)	IS 1661:1972	1.389 W/m.K	957.91 J/kg.K 1.315 MJ/m^{3}K	ISO 22007-2	ASTM C 1363
Hollow Clay Brick	400 X 200 X 100 mm	IS: 3952-1988	0.635 W/m.K	872.96 J/kg.K 1.215 MJ/m^{3}K		

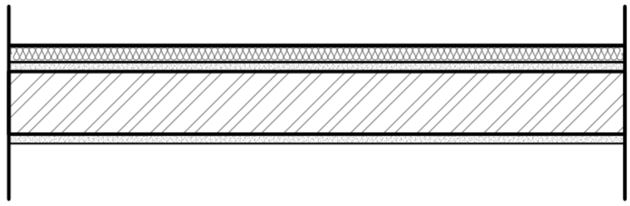
23. Hollow Clay Brick (100 mm thk) Wall with XPS board on one side and Cement Plaster

Total wall thickness= 158 mm

U value of the assembly= 0.89 W/m^2K



Elevation **Section**



Plan

Figure 108: Schematic drawings of hollow clay bricks (100 mm) wall with extruded polysterene board on one side and cement plaster coat on both sides

Table 30 : Walling technology and testing details for hollow clay bricks (100 mm) wall with extruded polysterene board on one side and cement plaster coat on both sides

<table>
<tr><th rowspan="2">Particulars</th><th rowspan="2">Dimensions</th><th rowspan="2">Specification</th><th colspan="2">Properties</th><th colspan="2">Testing Method</th></tr>
<tr><th>Conductivity</th><th>Specific heat</th><th>Particulars</th><th>Total Wall assembly</th></tr>
<tr><td>Cement Screed</td><td>2 mm thick</td><td></td><td></td><td></td><td></td><td rowspan="5">ASTM C 1363</td></tr>
<tr><td>PVC Film</td><td>1 mm thick</td><td></td><td></td><td></td><td></td></tr>
<tr><td>Extruded Ploysterene (XPS) Board</td><td>25 mm thick</td><td>ASTM C578-19</td><td>0.0316 W/m.K</td><td>Not Applicable</td><td>ASTM C 518</td></tr>
<tr><td>Cement Plaster mix (for both sides)</td><td>15 mm thick (cement: sand in 1:1 ratio)</td><td>IS 1661:1972</td><td>1.389 W/m.K</td><td>957.91 J/kg.K
1.315 MJ/m^{3}K</td><td rowspan="2">ISO 22007-2</td></tr>
<tr><td>Hollow Clay Brick</td><td>400 X 200 X 100 mm</td><td>IS: 3952-1988</td><td>0.635 W/m.K</td><td>872.96 J/kg.K
1.215 MJ/m^{3}K</td></tr>
</table>

24. Hollow Clay Brick (200 mm thk) Wall with Rockwool insulation infill and Cement Plaster

Total wall thickness= 230 mm

U value of the assembly= 1.83 W/m^{2}K

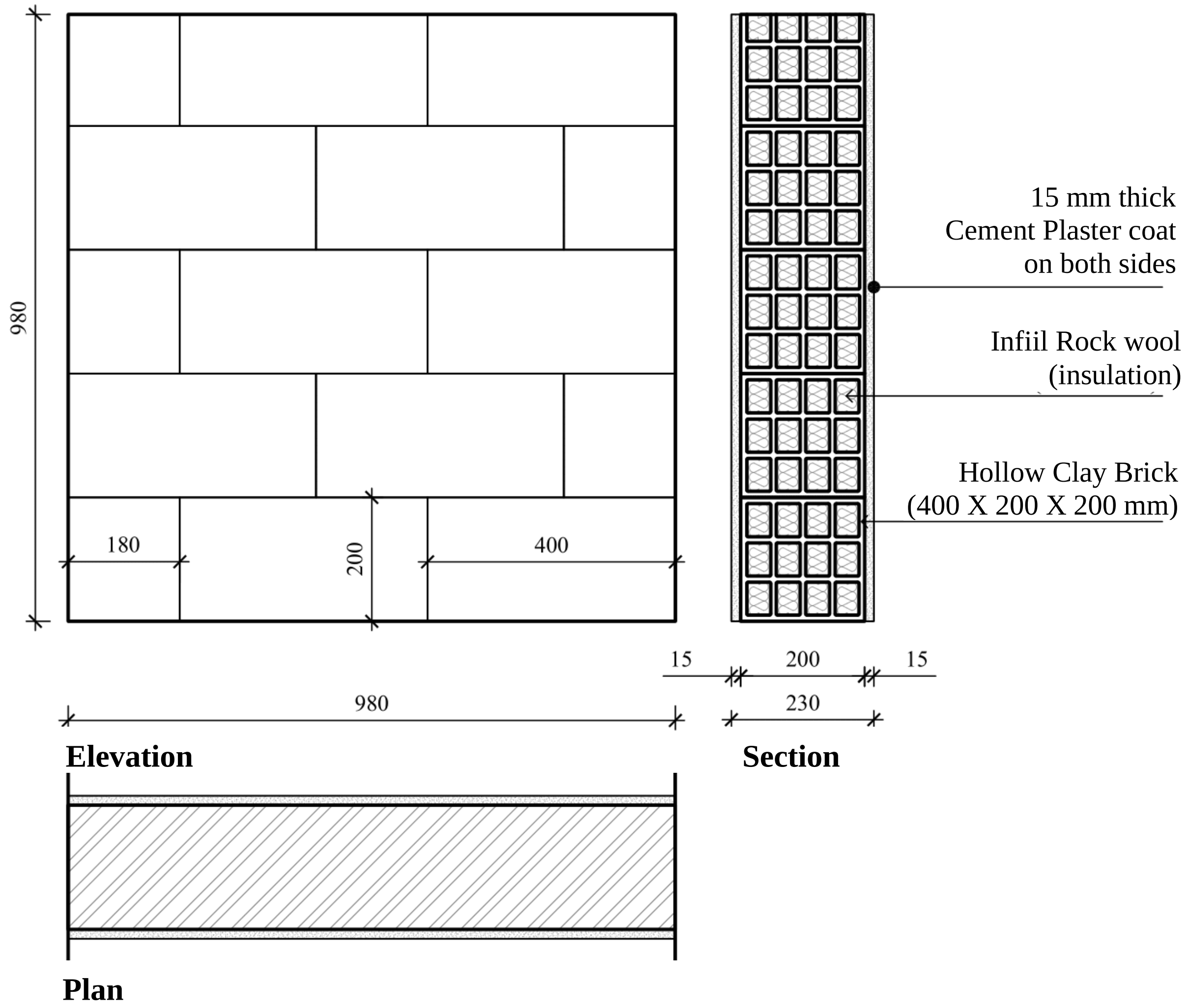


Figure 109: Schematic drawings of hollow clay bricks (200 mm) wall with rockwool insulation infill and cement plaster

Table 31: Walling technology and testing details for hollow clay bricks (200 mm) wall with rockwool insulation infill and cement plaster

Particulars	Dimensions	Specification	Properties		Testing Method	
			Conductivity	Specific heat	Particulars	Total Wall assembly
Cement Plaster mix (for both sides)	15 mm thick (cement: sand in 1:1 ratio)	IS 1661:1972	1.389 W/m.K	957.91 J/kg K 1.315 MJ/m^{3}K	ISO 22007-2	ASTM C 1363
Infill Rockwool (insulation)	Not Applicable	IS 8183:1993; BS EN 13162:2012	0.039 W/m.K	Not Applicable	ASTM C 518	

Hollow Clay Brick	400 X 200 X 200 mm	IS: 3952-1988	0.635 W/m.K	872.96 J/kg K	ISO 22007-2

25. Hollow Clay Brick (200 mm thk) Wall with Cement Plaster

Total wall thickness= 230 mm

U value of the assembly= 1.28 W/m^{2}K

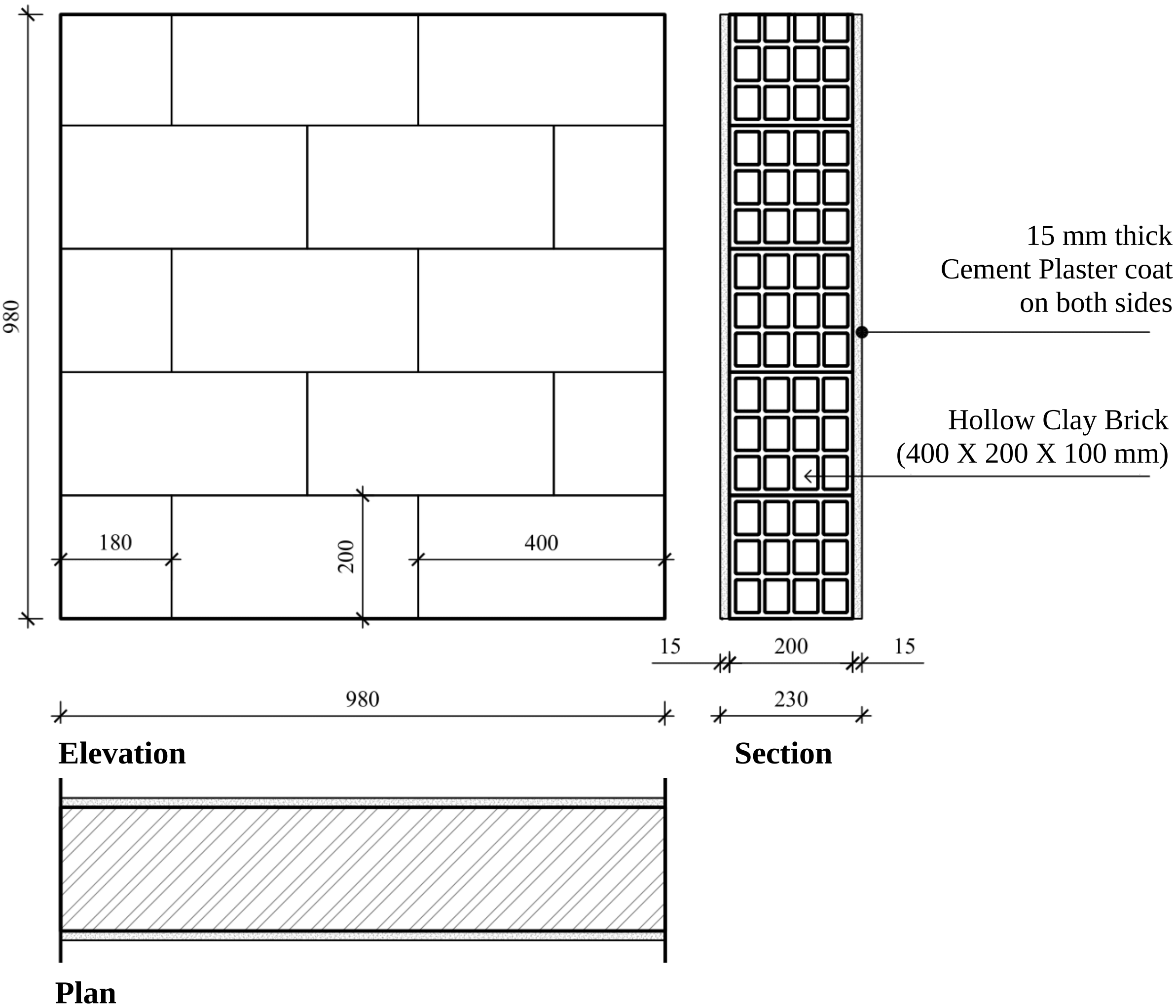


Figure 110 : Schematic drawings of hollow clay (100 mm) brick with cement plaster

Table 32 : Walling technology and testing details for hollow clay (100 mm) brick with cement plaster

Particulars	Dimensions	Specification	Properties: Conductivity	Properties: Specific heat	Testing Method: Particulars	Testing Method: Total Wall assembly
Cement Plaster mix (for both sides)	15 mm thick (cement: sand in 1:1 ratio)	IS 1661:1972	1.389 W/m.K	957.91 J/kg.K 1.315 MJ/m^{3}K	ISO 22007-2	ASTM C 1363
Hollow Clay Brick	400 X 200 X 200 mm	IS: 3952-1988	0.635 W/m.K	872.96 J/kg.K 1.215 MJ/m^{3}K		

26. Hollow Clay Brick (200 mm thk) Wall with Extruded Polystyrene (XPS) on one side and Cement Plaster

Total wall thickness= 258 mm

U value of the assembly= 0.75 W/m^{2}K

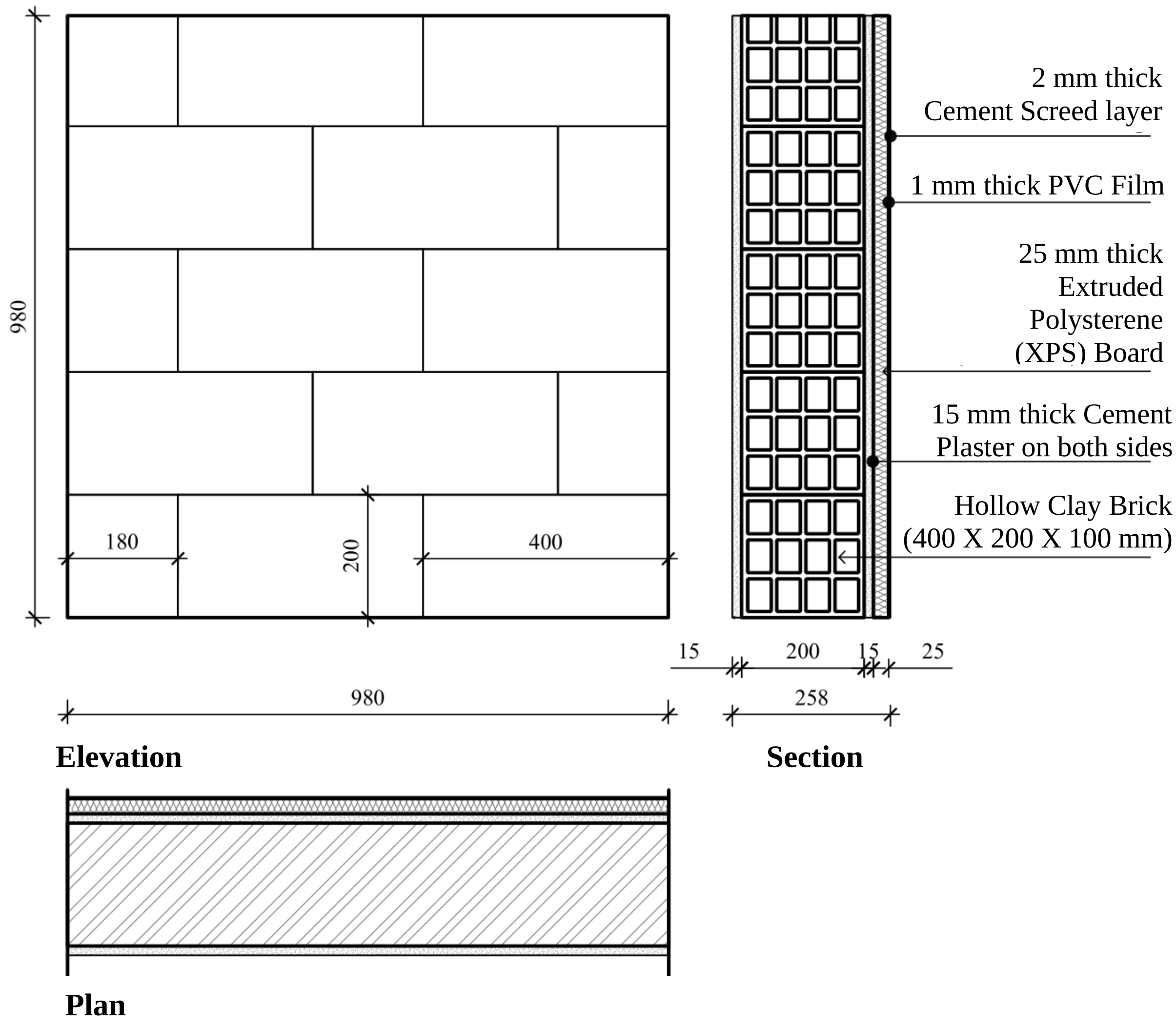


Figure 111 : Schematic drawings of hollow clay (200 mm) brick with XPS on one side and cement plaster coat on both sides

Table 33:Walling technology and testing detaibls for hollow clay (200 mm) brick with XPS on one side and cement plaster coat on both sides

Particulars	Dimensions	Specification	Properties		Testing Method	
			Conductivity	Specific heat	Particulars	Total Wall assembly
Cement Screed	2 mm thick					ASTM C 1363
PVC Film	1 mm thick					
Extruded Ploysterene (XPS) Board	25 mm thick	ASTM C578-19	0.0316 W/m.K	Not Applicable	ASTM C 518	
Cement Plaster mix	15 mm thick (cement: sand in 1:1 ratio)	IS 1661:1972	1.389 W/m.K	957.91 J/kg.K 1.315 MJ/m^3K	ISO 22007-2	
Hollow Clay Brick	400 X 200 X 200 mm	IS: 3952-1988	0.635 W/m.K	872.96 J/kg.K 1.215 MJ/m^3K		

27. RCC Wall (100 mm thk)

Total wall thickness= 100 mm

U value of the assembly= 3.59 W/m^2K

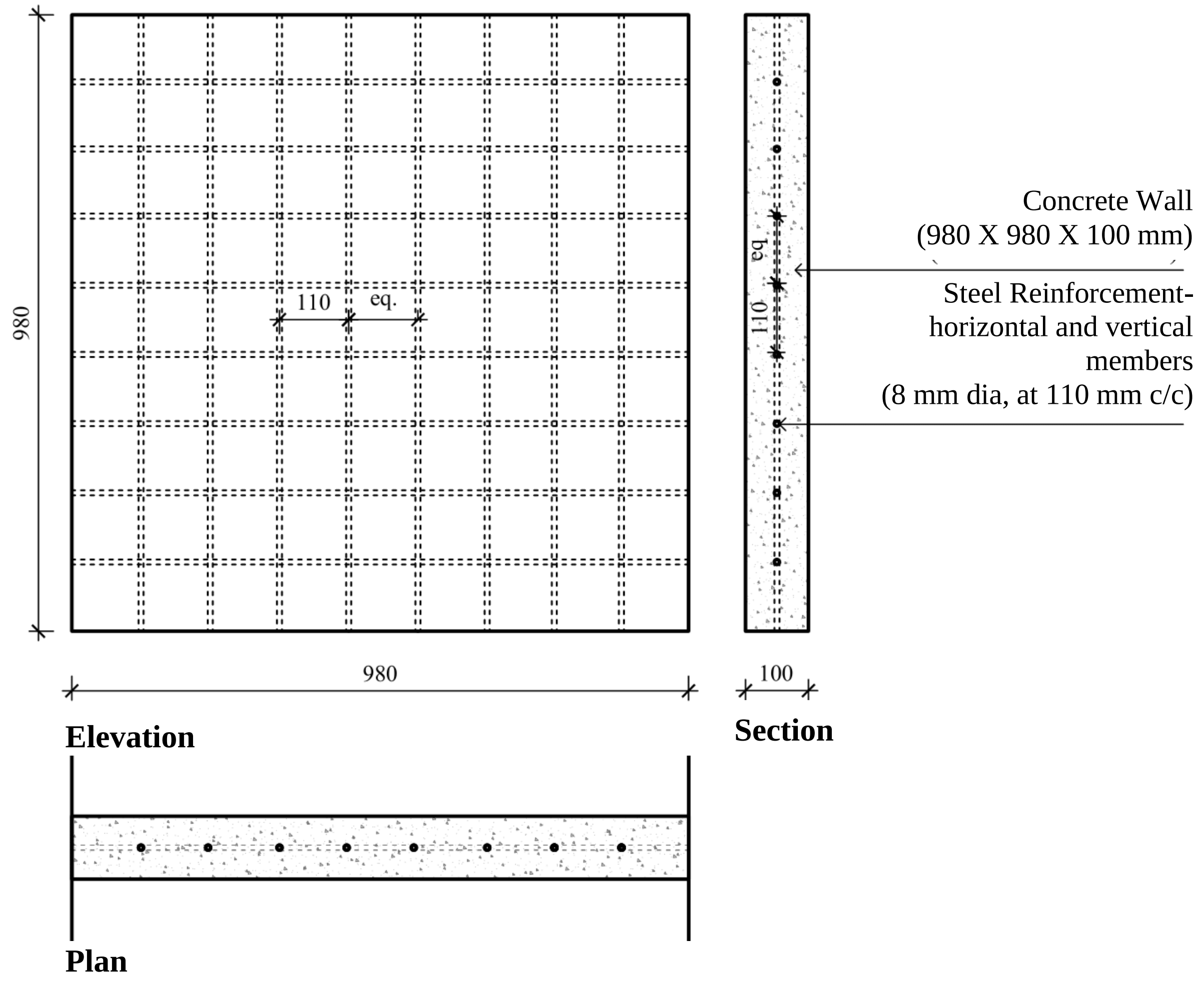


Figure 112: Schematic drawings of 100 mm thick RCC Wall

Table 34 : Walling technology and testing details for RCC Wall

Particulars	Dimensions	Specification	Properties		Testing Method	
			Conductivity	Specific heat	Particulars	Total Wall assembly
Steel Reinforcement	8 mm dia, @ 110 mm C/C	IS: 2062 (Grade A)				ASTM C 1363
Concrete Mix	100 mm thick	IS: 456-2000	1.5831 W/m.K	942.484 J/kg.K 1.6891 MJ/m^3K	ISO 22007-2	

28. RCC Wall (100 mm thk) with Expanded Polystyrene (EPS) board on one side

Total wall thickness= 153 mm

U value of the assembly= 0.58 W/m^2K

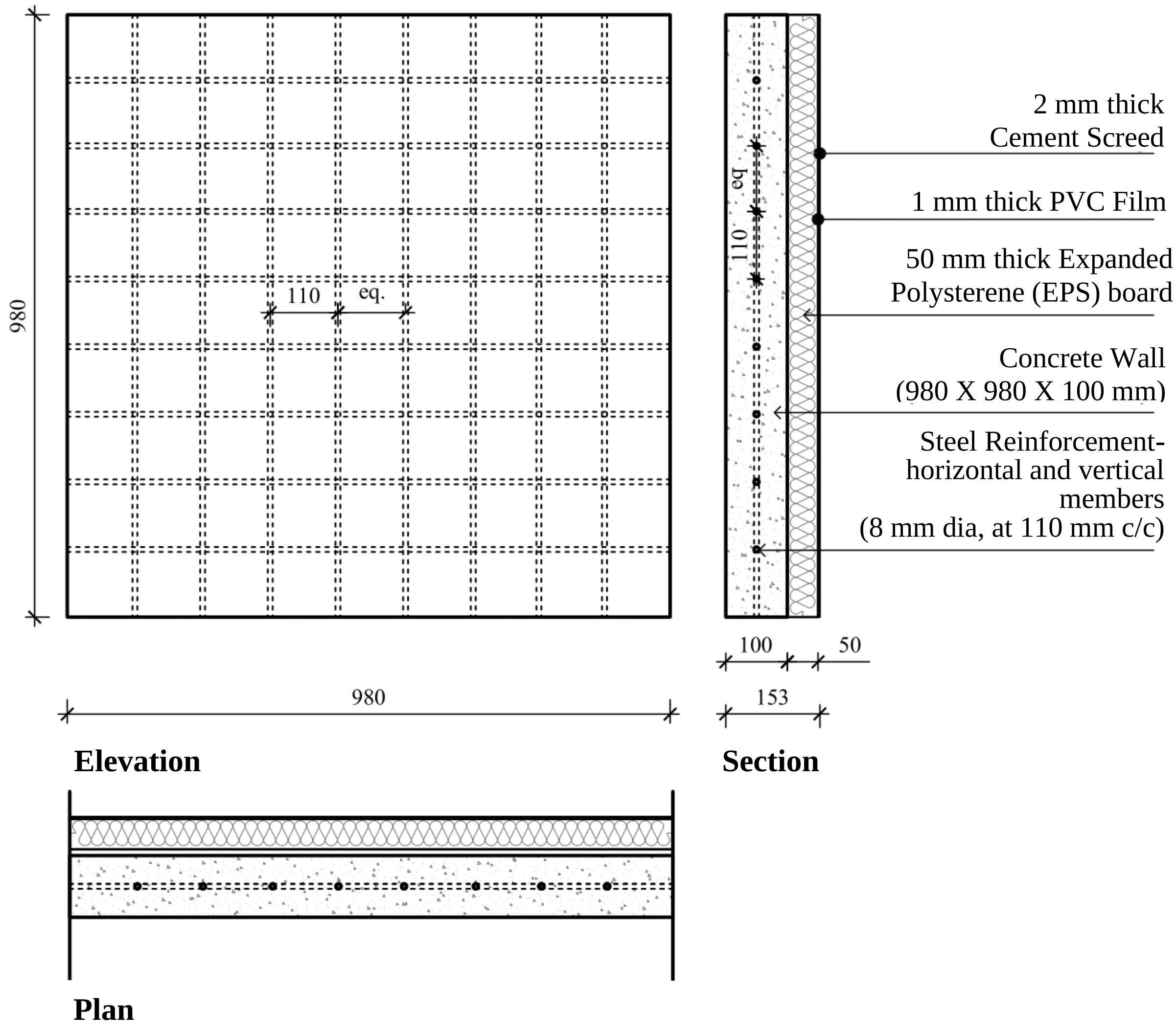


Figure 113 : Schematic drawings of 100 mm thick RCC Wall with EPS board on one side

Table 35: Walling technology and testing details for RCC Wall with EPS board on one side

Particulars	Dimensions	Specification	Properties: Conductivity	Properties: Specific heat	Testing Method: Particulars	Testing Method: Total Wall assembly
Cement Screed	2 mm thick					
PVC Film	1 mm thick					
Expanded Ploysterene (EPS) Board	50 mm thick	IS: 4671-1984	0.0365 W/m.K	Not Applicable	ASTM C 518	ASTM C 1363
Steel Reinforcement	8 mm dia, at 110 mm c/c	IS: 2062 (Grade A)				
Concrete Mix	100 mm thick	IS: 456-2000	1.5831 W/m.K	942.484 J/kg.K 1.6891 MJ/m^3K	ISO 22007-2	

29. RCC Wall (100 mm thk) with Styrofoam (EPS) board on both sides

Total wall thickness= 154 mm

U value of t-he assembly= 0.65 W/m^{2}K

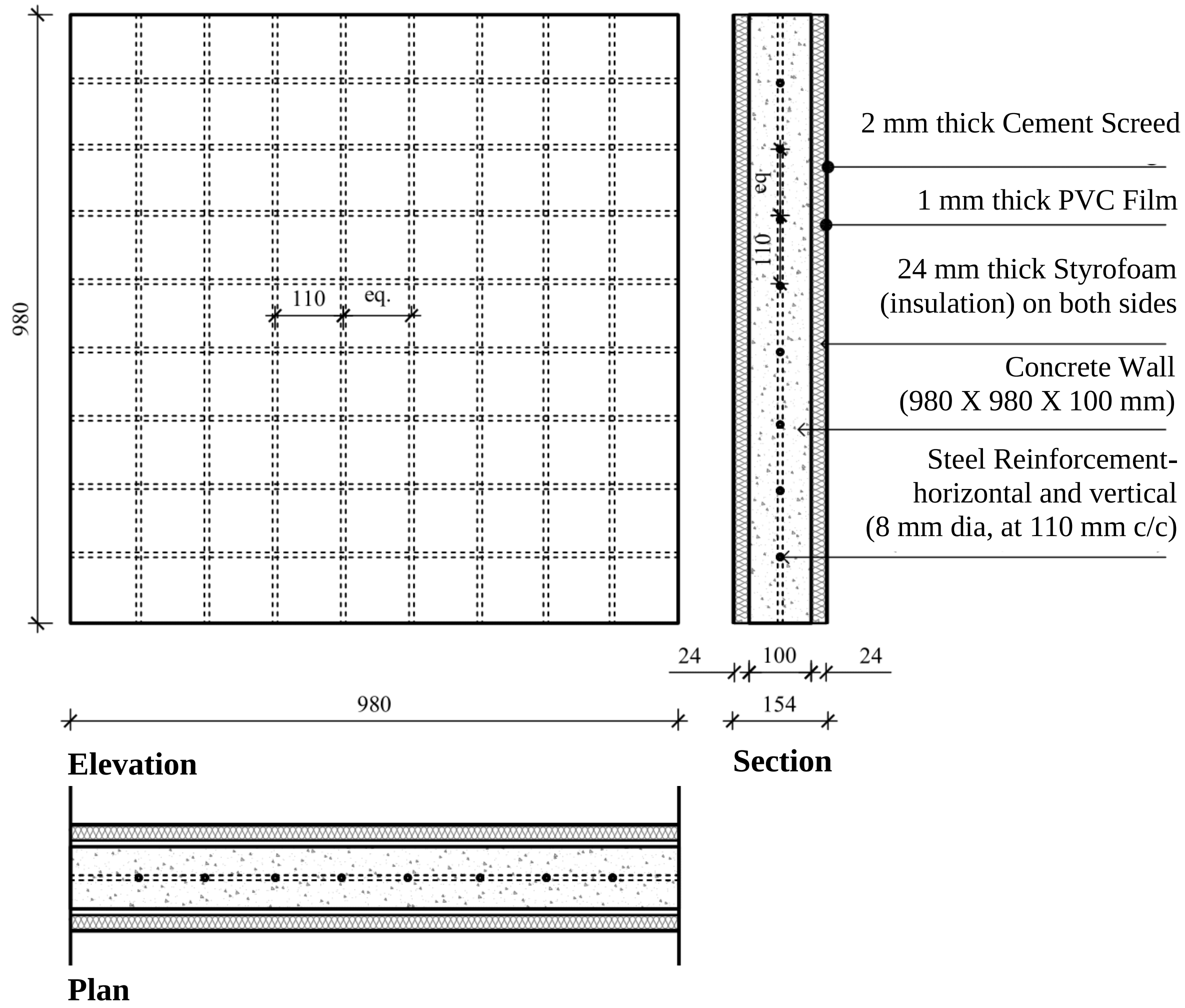


Figure 114 : Schematic drawings of 100 mm thick RCC Wall with Styrofoam (EPS) on both sides

Table 36:Walling technology and testing details for RCC Wall with Styrofoam (EPS) on both sides

Particulars	Dimensions	Specification	Properties		Testing Method	
			Conductivity	Specific heat	Particulars	Total Wall assembly
Cement Screed	2 mm thick					ASTM C 1363
PVC Film	1 mm thick					
Styrofoam Board (insulation)	24 mm thick	IS: 4671-1984	0.0352 W/m.K	Not Applicable	ASTM C 518	
Steel Reinforcement	8 mm dia, at 110 mm c/c	IS: 2062 (Grade A)				
Concrete Mix	100 mm thick	IS: 456-2000	1.5831 W/m.K	942.484 J/kg.K 1.6891 MJ/m^{3}K	ISO 22007-2	

30. RCC Wall (100 mm thk) with Polyvinyl Chloride (PVC) boards on both sides

Total wall thickness= 112 mm

U value of the assembly= 2.62 W/m^2K

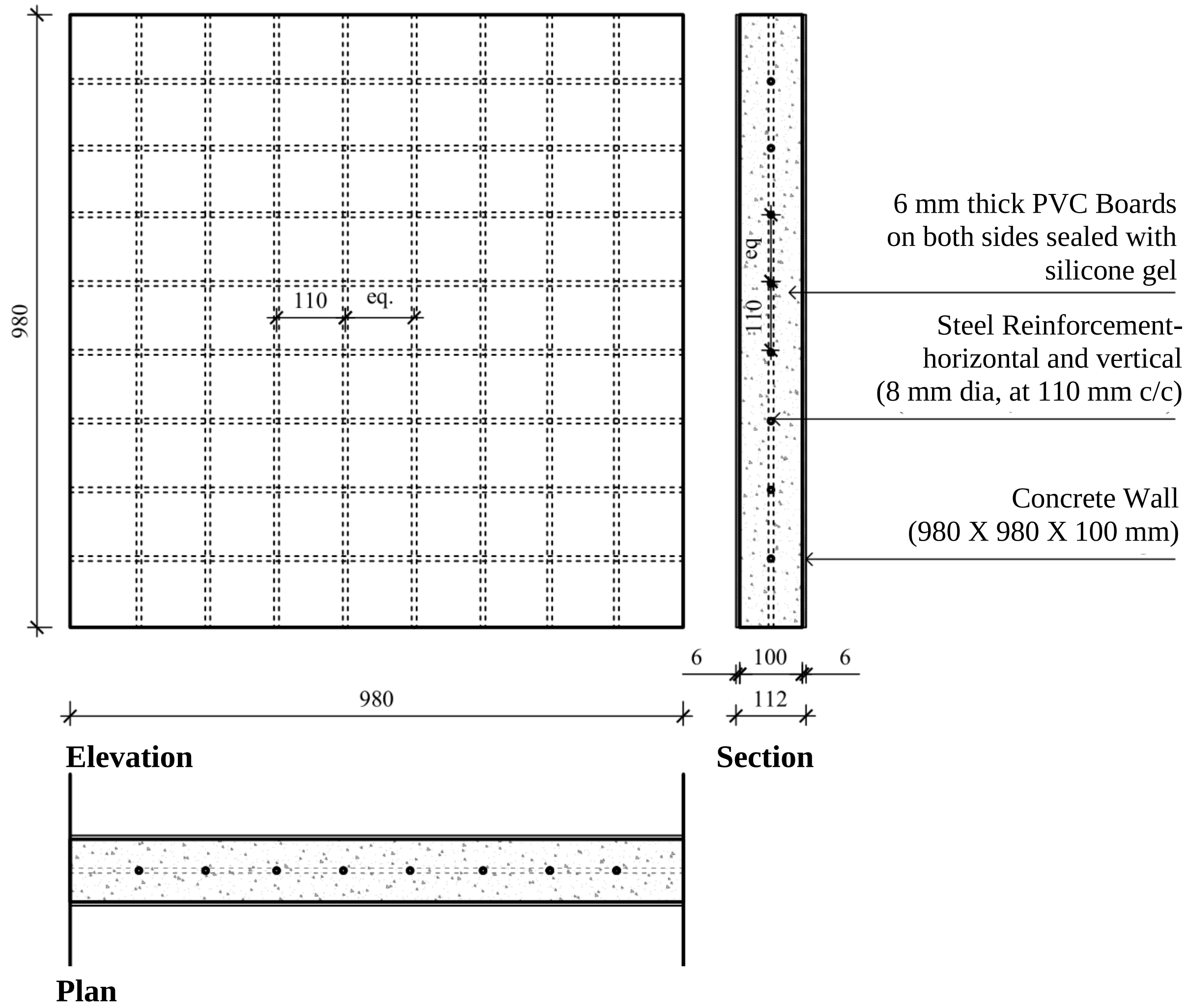


Figure 115: Schematic drawings of 100 mm thick RCC Wall with PVC boards on both sides

Table 37: Walling technology and testing details for RCC Wall with PVC boards on both sides

Particulars	Dimensions	Specification	Properties		Testing Method	
			Conductivity	Specific heat	Particulars	Total Wall assembly
PVC Board sealed with silicone gel	6 mm thick		0.084 W/m.K	0.3468 MJ/m^3K		
Steel Reinforcement	8 mm dia, @ 110 mm C/C	IS: 2062 (Grade A)			ISO 22007-2	ASTM C 1363
Concrete Mix	100 mm thick	IS: 456-2000	1.5831 W/m.K	942.484 J/kg.K 1.6891 MJ/m^3K		

31. RCC Wall (100 mm thk) with Expanded Polystyrene (EPS) board on one side and Polyvinyl Chloride (PVC) board on both sides

Total wall thickness= 165 mm

U value of the assembly= 0.52 W/m^{2}K

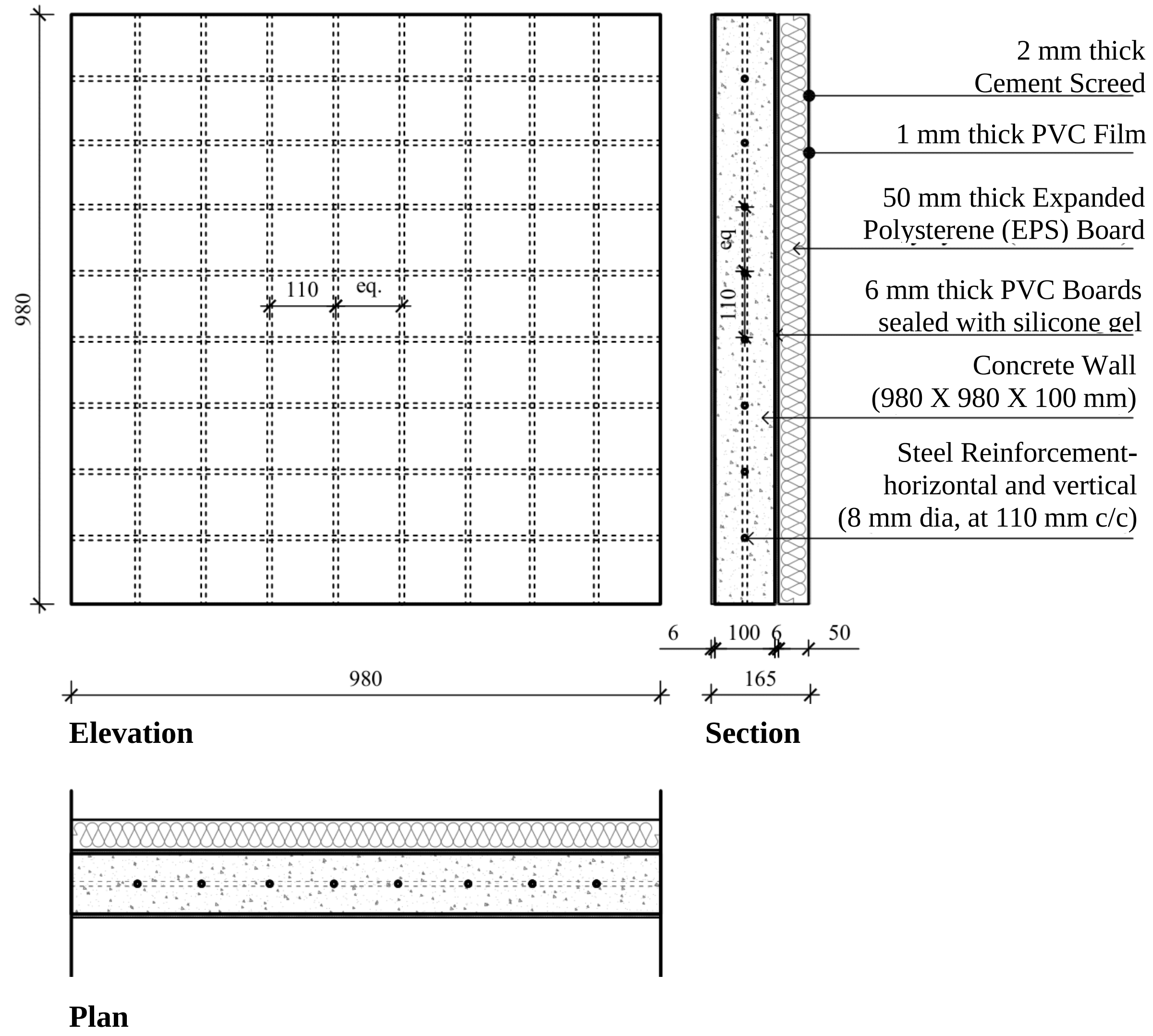


Figure 116:Schematic drawings of 100 mm thick RCC Wall with EPS insulation board on one side and PVC boards on both sides

Table 38 : Walling technology and testing details for RCC Wall with EPS insulation board on one side and PVC boards on both sides

<table>
<tr><th rowspan="2">Particulars</th><th rowspan="2">Dimensions</th><th rowspan="2">Specification</th><th colspan="2">Properties</th><th colspan="2">Testing Method</th></tr>
<tr><th>Conductivity</th><th>Specific heat</th><th>Particulars</th><th>Total Wall assembly</th></tr>
<tr><td>Cement Screed</td><td>2 mm thick</td><td></td><td></td><td></td><td></td><td rowspan="7">ASTM C 1363</td></tr>
<tr><td>PVC Film</td><td>1 mm thick</td><td></td><td></td><td></td><td></td></tr>
<tr><td>Expanded Polysterene (EPS) Board</td><td>24 mm thick</td><td>IS: 4671-1984</td><td>0.0365 W/m.K</td><td>Not Applicable</td><td>ASTM C 518</td></tr>
<tr><td>PVC Board</td><td>6 mm thick</td><td></td><td>0.084 W/m.K</td><td>0.3468 MJ/m^2K</td><td rowspan="4">ISO 22007-2</td></tr>
<tr><td>Steel Reinforcement</td><td>8 mm dia, @ 110 mm C/C</td><td>IS: 2062 (Grade A)</td><td></td><td></td></tr>
<tr><td rowspan="2">Concrete Mix</td><td rowspan="2">100 mm thick</td><td rowspan="2">IS: 456-2000</td><td rowspan="2">1.5831 W/m.K</td><td>942.484 J/kg.K</td></tr>
<tr><td>1.6891 MJ/m^3K</td></tr>
</table>

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Advancing Building Energy Efficiency in India

Part-III: Derivation of Thermal Transmittance Value of Roofing Technologies

APRIL 2024

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Construction Agency

THUMBIMPRESSIONS

Part III: Derivation of Thermal Transmittance Values of Roofing Technologies

April 2024

Shakti Sustainable Energy Foundation

CEPT Research and Development Foundation,
CEPT University

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Disclaimer

CEPT Research and Development Foundation does not endorse any of the products or technologies mentioned in this document.

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ABBREVIATIONS

CARBSE	Centre for Advanced Research in Building Science and Energy
CRDF	CEPT Research and Development Foundation
PUF	Polyurethane Foam
GHB	Guarded Hot Box
PPGI	Pre-painted Galvanized Iron
XPS	Extruded Polystyrene

UNITS AND PARAMETERS

Thermal Transmittance Value (U- Value) : **W/m^{2}K**

Relative Humidity (RH) : **%**

Specific heat per unit mass : **J/kg.K**

Specific heat per unit volume : **MJ/m^3.K**

Thermal Conductivity : **W/m.K**

1. Introduction

This report submitted by CRDF, CEPT University aims to facilitate knowledge regarding thermal performance evaluation of roof construction technologies through the derivation of their U-values, using its state-of-the-art laboratory facilities. To validate their U-value test results for a dependable reference in sustainable building practices, the research activity protocol has been listed in Figure1.
This database has been envisaged to facilitate efficient and sustainable affordable housing construction
This research activity tests ten roofing assemblies that may fall in one of the following categories:

- **Conventional Roofing Technologies**: This includes business-as-usual roof assemblies such as RCC slabs, Precast Hollow core slab, decking slab etc. that can be used as reference baselines.
- **Alternative Roofing Technologies**: This category includes region-specific roofing assemblies used in vernacular architecture such as various kinds of Mangalore tiled roofs, thatch roofs etc.
- **Emerging Roofing Technologies**: This category refers to industrialized roofing technologies, systems, and/ or products such as Tepper quad bubble deck, Light weight steel gauge roofing etc.

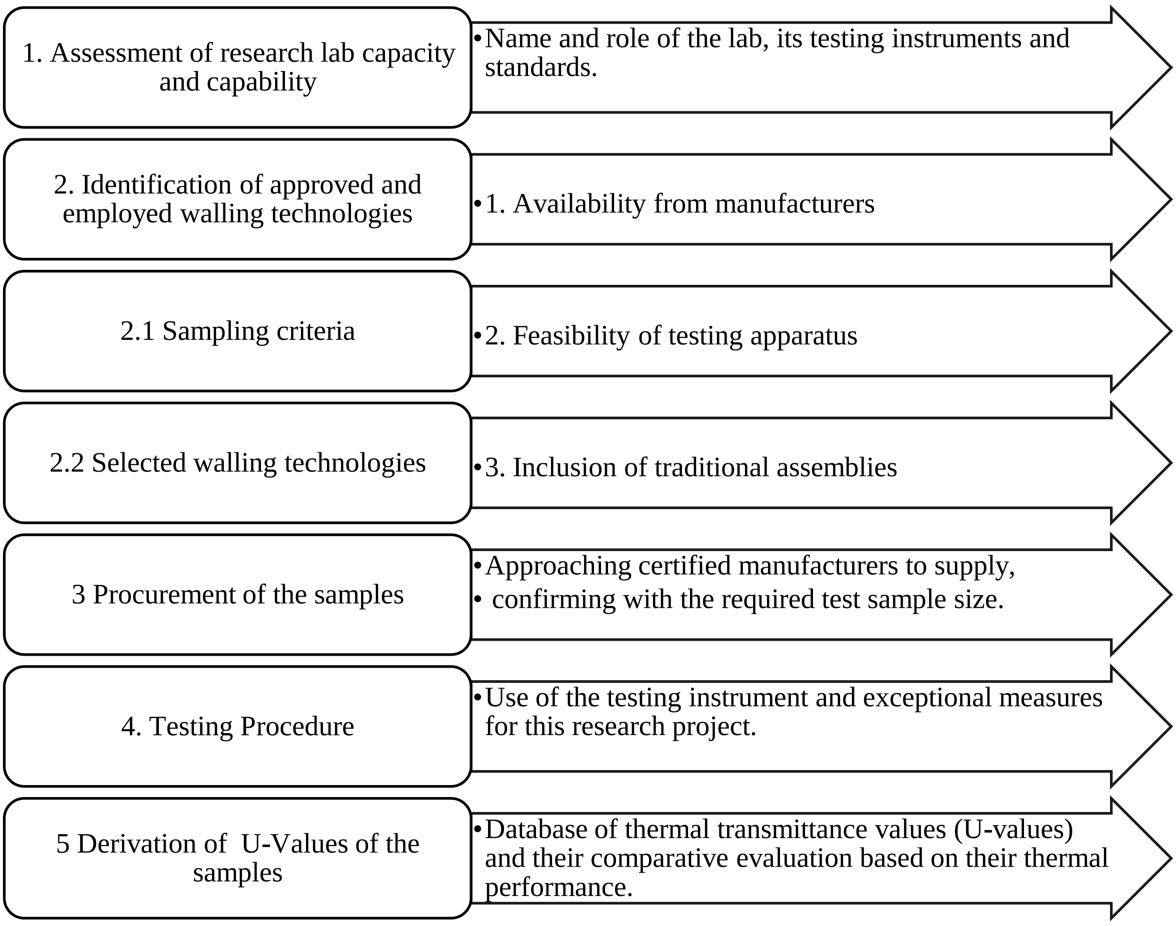


Figure 1: Project Outline and research activity protocol

2. Assessment of Research Instruments

2.1 Guarded Hot Box (GHB)

Centre for Advanced Research in Building Science and Energy (CARBSE), under CRDF, CEPT University, Ahmedabad has characterized and tested the roofing technology samples procured from different manufacturers using Guarded Hot Box (GHB), as per ASTM C1363.

GHB is used to test the thermal performance of non-homogenous specimens, such as complex wall assemblies, cavity walls, ventilated shaded wall assembly or walls with phase change materials (PCM). It determines the amount of heat transfer through a given material or assembly of various materials. This is done by controlling the temperature on both sides of the material and minimizing the extraneous heat transfers that takes place through material other than the given one; which can be used to determine the thermal transmittance of a homogeneous as well as a non-homogenous specimen and can test a specimen with a maximum thickness of 350mm.

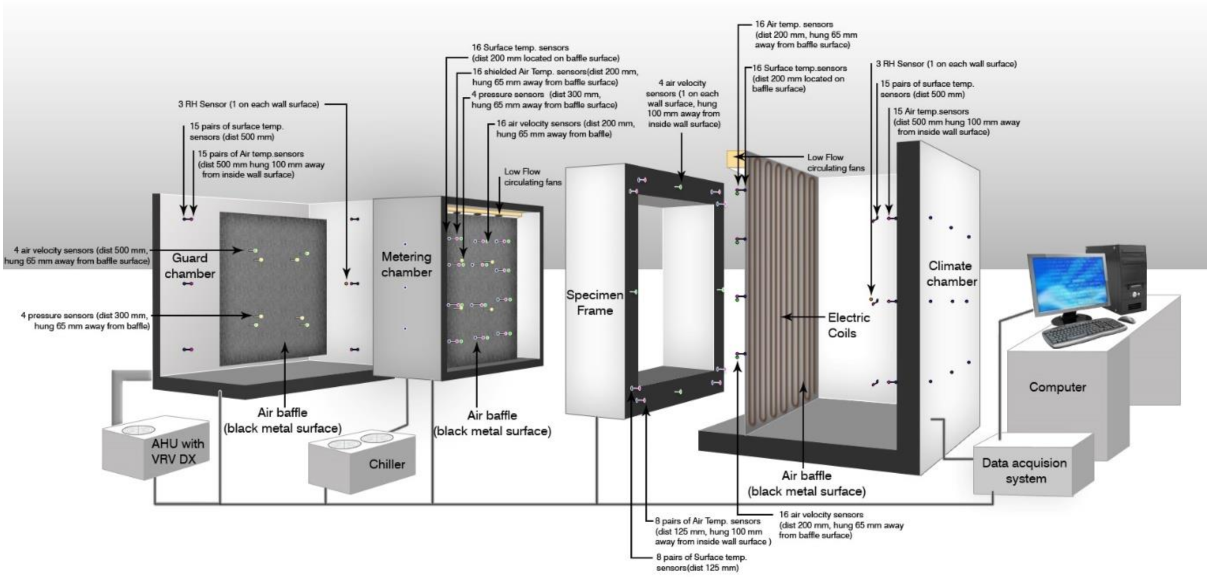


Figure 2: Exploded View of the Guarded Hot Box Apparatus

The metering chamber is cooled using a chiller and the guard chamber is maintained at the same temperature using an HVAC system. The climatic chamber is maintained at higher temperatures using electric coils. Surface, water and air temperature sensors are placed for temperature control along with relative humidity (RH), pressure, and air velocity sensors placed at equal distances. The GHB used for testing is custom made as per ASTM C1363. The range of measurement is 0.1 to 5 W/m2k and the specimen size must have a maximum width of 980 mm, length of 980 mm and thickness up to 350 mm (CBERD, 2014). Figure 2 is a photograph showing the assembly of GHB at CARBSE. The testing procedure is further elaborated in Section 3 of this report

3. Testing Procedure

3.1. General Procedure

The GHB apparatus is traditionally recognized as the only absolute method for thermal conductivity measurement in a steady state for homogeneous and non-homogeneous materials. To determine the net energy flow through the specimen, a five sided metering box is placed with the open side against the warm face of the test panel. Apparently, if there is no net energy exchange across the walls other than that of the metering box, and only negligible flanking loss around the specimen, the heat input from the fan and heaters, minus any cooling coil energy extraction from the metering box, would be considered a measure of the energy flux through the metered area of the specimen. Since it is not practically possible to have the condition mentioned above, the GHB apparatus is designed to obtain an accurate measure of the net sample heat flow. Here, the net energy transfer through the specimen is determined from net measured energy input to the metering chamber, rectifying the losses through the chamber walls and flanking loss for the specimen at the perimeter of the metering area. The heat loss rate through the metering chamber walls is curbed by using highly insulated walls and controlling the surrounding ambient temperature, or by using a temperature controlled guard chamber. That portion of the specimen outside the boundary of the metering area or the specimen frame, exposed to the guarding space temperature, constitutes a passive guard to minimize the flanking heat flow in the test panel near the perimeter of the metering area. The basic hot box apparatus can be assembled in a wide variety of sizes, orientations, and designs. There are two primary design configurations. The first is the guarded hot box used for the testing, that has a controlled “guard” chamber surrounding the metering box. An example of this configuration is presented in Figure 4 (ASTM, n.d.).

Figure 3 Photographs of the metering chamber attached to the specimen frame and the entire

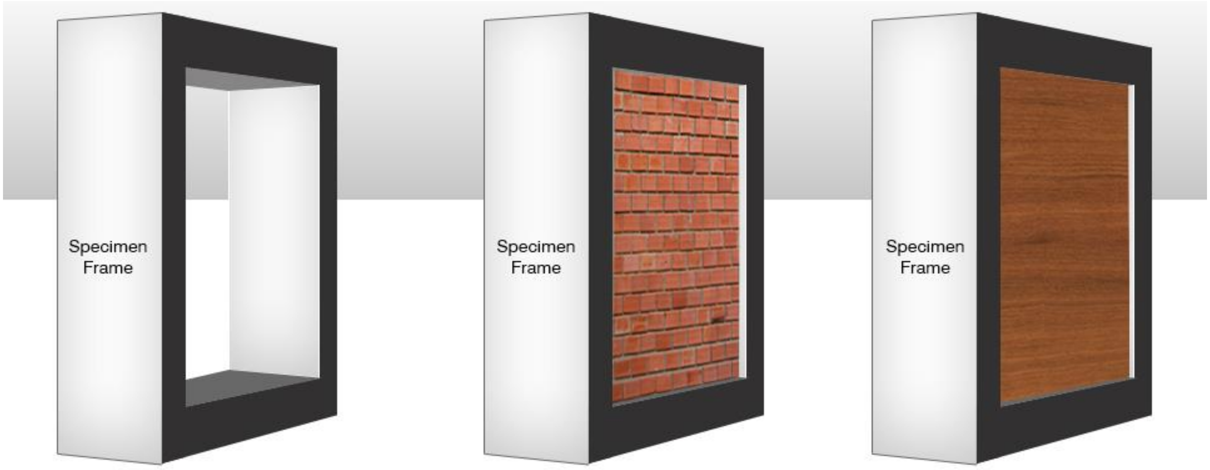


Figure 4: 3D showing the specimen frame

Figure 5: Thatch Roofing Assembly in the GHB specimen frame apparatus

4. Identification of the Roofing Assembly

4.1 Sampling Criteria

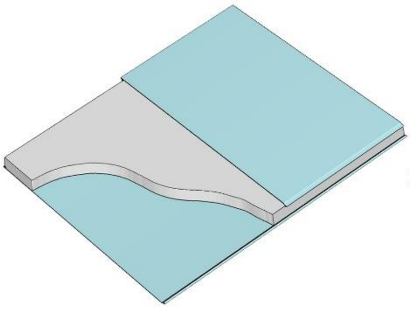
1. **Availability from Manufacturers**: Samples were sourced from manufacturers who had the product readily available for procurement.
2. **Manufacturers:** Preference was given to manufacturers who were willing to provide roofing samples of the specified dimensions (980mm x 980mm) to accommodate the GHB instrument's specimen frame for testing purposes.
3. **Inclusion of Traditional Techniques:** Samples were chosen from materials and techniques that reflect traditional roofing practices currently utilized in both vernacular and contemporary green building methodologies in India.
4. **Feasibility for Testing Apparatus:** The selection of technology and materials was contingent upon their feasibility to be constructed into samples that seamlessly fit within the testing apparatus frame. It was crucial that such construction did not necessitate alterations to the inherent properties of the materials or deviate from the regional construction methodologies.

4.2 Selected Roofing Technologies

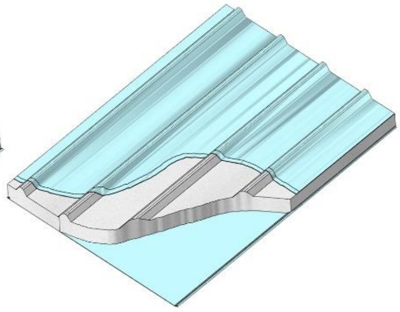
Non-homogeneous and low-cost roofing construction techniques/technologies, such as Mangalore tiles roof, thatch roof were tested along with selected roofing technologies to understand the comparative assessment between the traditional and the advanced technologies. Technologies selected for testing are specified in Table 1. This following order is listed according to the testing sequence. Refer to Annexures 1 and 2 for more information on the assemblies.

Table 1: Selected Roofing Assemblies for testing

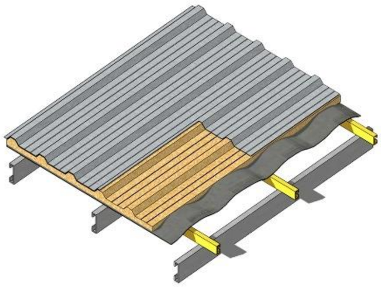
Phase	Sr. No	Roofing Assembly
I	1	Flat PUF-insulated roof panels with PPGI sheet
	2	Curved PUF-insulated roof panels with PPGI sheet
	3	TRIMDEK Profile with PUF insulation and aluminum sheet waterproofing
	4	Timber + Single sided Mangalore tile roofing
	5	Timber + Double sided Mangalore tile roofing
	6	Bamboo + Single sided Mangalore tile roofing
	7	Bamboo + Double sided Mangalore tile roofing
	8	Thatch roof
	9	Thatch roof + 75mm XPS insulation
	10	Timber + Single sided Mangalore tile roofing + Cement Fiber Board



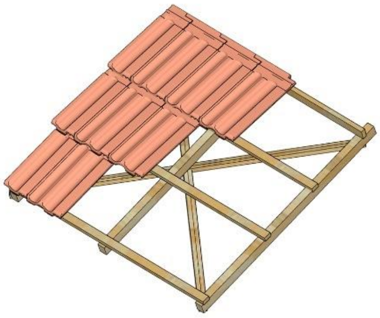
PUF-insulated roof panels with Flat top PPGI sheet (pre-painted galvanized iron)



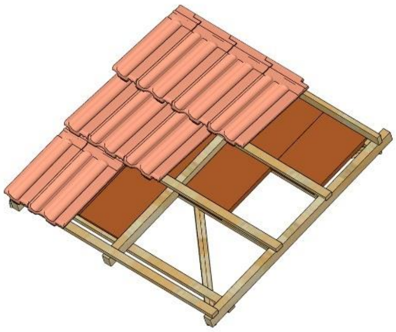
PUF-insulated roof panels with curved top PPGI sheet (pre-painted galvanized iron)



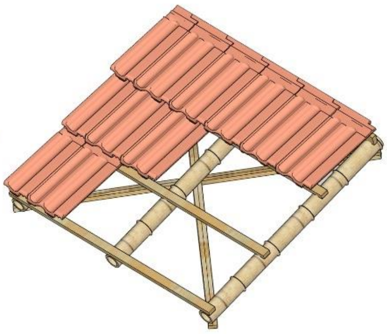
TRIMDEK Single skin with PUF insulation and aluminum sheet vapor barrier



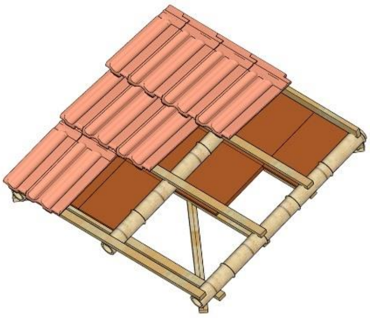
Timber with single sided mangalore tiles roofing



Timber with double sided mangalore tiles roofing



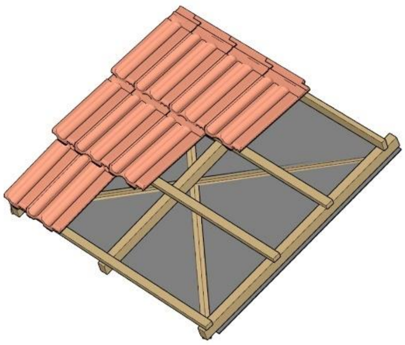
Bamboo with single sided mangalore tiles roofing



Bamboo with double sided mangalore tiles roofing

Thatch roofing assembly

Thatch roof with XPS insulation



Timber with single sided mangaloe tiles roofing + Cement Fiber Board

Figure 6: Selected roofing assembly for testing

4.3 Selected Roofing Technologies

For the Phase I of the report, we have a mix of industrial and vernacular assemblies. The industrial assemblies were procured from the manufacturer while the traditional roofing systems had to be constructed in the prevalent vernacular way of construction, employing skilled artisans with expert guidance for the results that can be applied. Thus, the execution serviced were rendered by Thumbimpressions LLP, a firm specialized in bamboo & earth construction innovations, artisan training and R&D. The vernacular assemblies selected for the Phase I were all dry construction assemblies, hence they were made by the artisans in the workshop and installed as a 980*980 panel directly into the GHB on the day of testing.

Table 2: List of Roofing technologies selected along with source region and manufacturer information

S/N	Technologies	Manufacturer/Construction Agency	Location
1	Flat PUF-insulated roof panels with PPGI sheet	KEON Cold-chain Evolution	Ahmedabad, Gujarat
2	Curved PUF-insulated roof panels with PPGI sheet		
3	TRIMDEK Profile with PUF insulation and aluminum sheet waterproofing	TATA blueScope Steel	
4	Timber + Single sided Mangalore tile roofing	**Technical coordinator:** Milind Zaveri **Second Party:** Thumbimpressions, Surat Gujarat. **Services:** 1. Execution of all the traditional roofing systems 2. Procuring local materials and coordinating with the artisans. 3. Transportation of the materials, artisans, and assembly supervisor. 4. Provide technical facilitation related to securing the roofing system into the apparatus.	
5	Timber + Double sided Mangalore tile roofing		
6	Bamboo + Single sided Mangalore tile roofing		
7	Bamboo + Double sided Mangalore tile roofing		
8	Thatch roof		
9	Thatch roof + XPS insulation		
10	Timber + Single sided Mangalore tile roofing + Cement Fiber Board		

5. Results

Table 3 shows the Thermal Transmittance values obtained for all 10 assemblies and Figure 5 shows evaluation of the thermal performances of the same.

Table 3: Thermal transmittance value database of all selected roofing assemblies and technologies.

S/N	Roof Types	Thickness (mm)	U-value (W/m^{2}K)
1	Flat PUF-insulated roof panels with PPGI sheet	121.4	0.253
2	Curved PUF-insulated roof panels with PPGI sheet	121.4	0.246
3	TRIMDEK Profile with PUF insulation and Aluminum sheet waterproofing	76.2	0.255
4	Timber + Single sided Mangalore tile roofing	93.0	1.505
5	Timber + Double sided Mangalore tile roofing	105.0	1.117
6	Bamboo + Single sided Mangalore tile roofing	108.0	1.502
7	Bamboo + Double sided Mangalore tile roofing	114.0	1.122
8	Thatch roof	246.0	0.234
9	Thatch roof + XPS insulation	321.0	0.177
10	Timber + Single sided Mangalore tile roofing + Cement Fiber Board	105.0	1.484

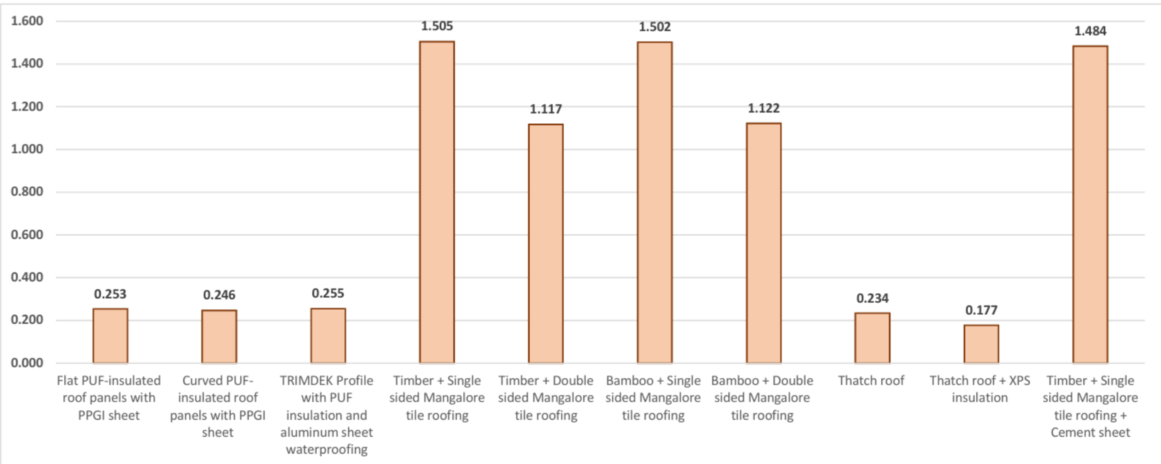


Figure 7: Thermal performance evaluation of the selected roof assemblies, lower the U-value, better the performance

6. Annexures

Annexure I: Summary of the Selected Roofing Technologies

This section is an elaboration on the types of roof samples procured and tested for thermal performance using GHB.

1. Flat PUF-insulated roof panels with PPGI sheet (Pre-painted galvanized iron)

Flat PPGI (Pre-Painted Galvanized Iron) sheet with PUF (Polyurethane Foam) insulated roof panels refers to a type of roofing material that combines insulation and a protective outer layer for buildings. PUF is a type of insulation material that is commonly used in construction. It is formed by combining two liquid components to create a foam, which is then used to insulate various building elements. PPGI is a type of steel sheet that has been coated with a layer of zinc to protect it from corrosion, and then further coated with a layer of paint for aesthetic purposes.

The roof panel typically consists of three main layers:
Outermost Layer (PPGI sheet): 0.7 mm thick PPGI sheet
This is the visible layer that provides protection against environmental elements such as sunlight, rain, and corrosion.
Insulation (PUF): 120 mm thick insulating layer
The polyurethane foam layer serves as insulation, helping to regulate the temperature within the building by minimizing heat transfer. The thickness of the roof panels can vary based on the specific requirements and the intended application. Thicker panels generally offer better insulation properties.
Innermost Layer (PPGI sheet): 0.7 mm thick PPGI sheet
This layer can provide additional structural support.

Use: These panels are primarily used as roofing material for various types of buildings, including commercial, industrial, and residential structures. Some of the advantages include ease of installation, durability, and corrosion resistance.

Figure 8: Project of a warehouse project constructed using Flat PPGI Sheet (Source: https://www.indiamart.com/proddetail/factory-shed-22308673388.html)

Assembly thickness: 121.4 mm | U-Value: 0.253 W/m²K

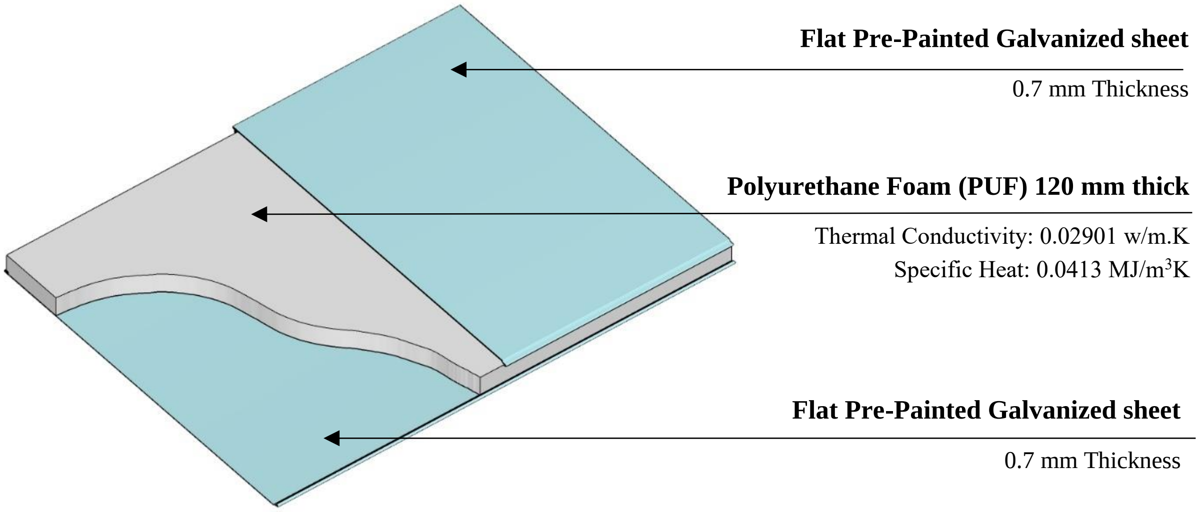


Figure 9: Illustration of Flat PUF Insulated roof panel with PPGI sheet sample used as the specimen for the test.

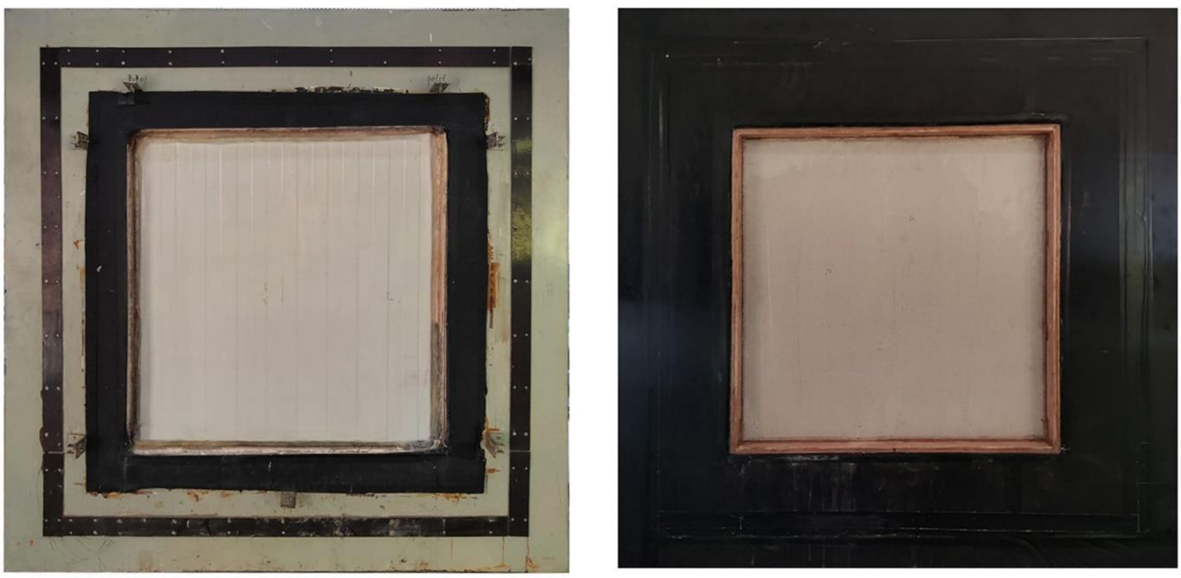


Figure 10:Photographs showing Front (left) and the back (right) of the Flat PPGI sheet with PUF Sheet insulation

2. Curved PUF-insulated roof panels with PPGI sheet (Pre-painted galvanized iron).

The Curved PPGI sheet with PUF insulated roof panels is similar to the Flat PPGI assembly but with ribbed roofing and wall cladding profile with subtle fluting in the pans to provide strength and long-spanning capabilities.

The roof panel typically consists of three main layers:
Outermost Layer (PPGI sheet): 0.7mm thick PPGI sheet
This is the visible layer that protects against environmental elements such as sunlight, rain, and corrosion.
Insulation (PUF): 80 - 120 mm thick insulating layer
The polyurethane foam layer serves as insulation, helping to regulate the temperature within the building by minimizing heat transfer. The thickness of the roof panels can vary based on the specific requirements and the intended application. Thicker panels generally offer better insulation properties.
Innermost Layer (PPGI sheet): 0.7mm thick PPGI sheet
This layer can provide additional structural support.

Use: These panels are primarily used as roofing material for various types of buildings, including commercial, industrial, and residential structures.

Figure 11:Project of an industrial shed constructed using curved PPGI Sheet

Source: https://www.indiamart.com/proddetail/badminton-court-roofing-sheds-shuttle-court-constructions-in-chennai-tamil-nadu-india-14464440797.html?pos=10&pla=n

Assembly thickness: 121.4 mm | U-Value: 0.246 W/m²K

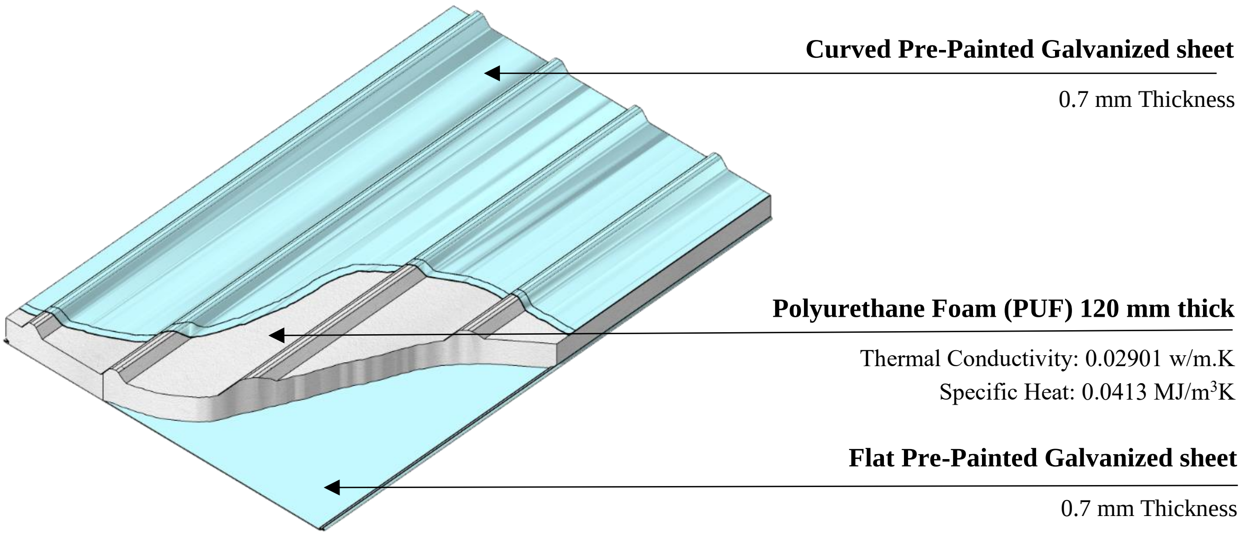


Figure 12: Illustration of Curved PUF Insulated roof panel with PPGI sheet sample used as the specimen for the test.

Figure 13: Photographs showing the Front (left) and the back (right) of Curved PPGI sheet with PUF Insulation within the GHB apparatus

3. TRIMDEK single skin Steel sheet with PUF insulation and Aluminium sheet vapour barrier

LYSAGHT TRIMDEK 1015 is a versatile, trapezoidal ribbed roofing and wall cladding profile with subtle fluting in the pans to provide strength and long spanning capabilities. It is ideal for industrial and commercial applications. It is manufactured from high strength steel and provides excellent spanning capability resulting in better design freedom. TRIMDEK is manufactured from Al-Zn alloy coated steel that offers excellent corrosion resistance and lasts up-to four times more than ordinary Zinc coated steel profiles. TRIMDEK profile comes with Solar Reflectance Technology that lowers surface temperature by absorbing lesser heat from the sun. It keeps both roofs & buildings cooler at reduced energy costs.

The roof panel typically consists of three main layers:
Outermost Layer : 0.7 mm thick Al-Zn Alloy coated steel sheet
This is the visible layer that provides protection against environmental elements such as sunlight, rain, and corrosion.
Insulation (PUF): 50-75 mm insulating layer
The polyurethane foam layer serves as insulation, helping to regulate the temperature within the building by minimizing heat transfer.
Innermost Layer (Aluminum sheet): 0.5 mm Aluminum sheet helped in waterproof insulation.

Use: These panels are primarily used as roofing material for various types of buildings, including commercial, industrial, and residential structures.

Figure 14: Project of an industrial shed constructed using TRIMDEK single skin PPGI sheet

Source: https://tatabluescopesteel.com/products-solutions/durashine/purlin/

Assembly thickness: 76.2 mm | U-Value: 0.255 W/m^{2}K

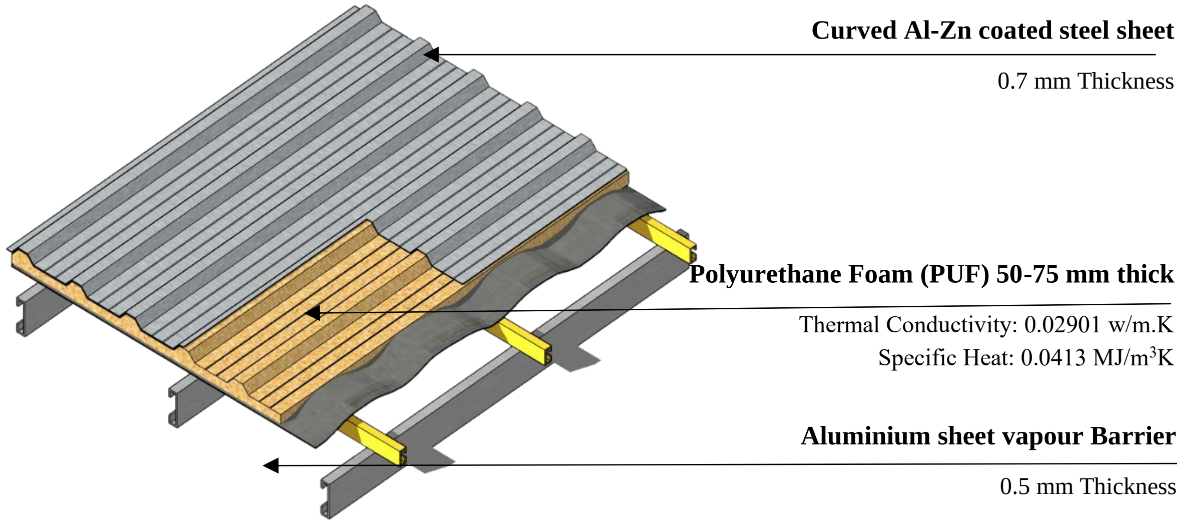


Figure 15: Illustration of TRIMDEK single skin PPGI sheet with PUF insulation and Aluminum sheet vapor barrier sample used as the specimen for the test.

Figure 16: Photographs showing the Front (left) and the back (right) of Curved PPGI sheet with PUF insulation within the GHB apparatus.

4. Timber + Single sided Mangalore tile roofing

The single-sided Mangalore tile roofing stands out as a foundational and widely embraced roofing style in India. Crafted from baked clay, Mangalore tiles exhibit remarkable qualities, inherently resisting moisture absorption and heat retention, making them both waterproof and heat-resistant. Beyond their durability, the design of these tiles ensures effective rainwater drainage, making them especially suited for regions with heavy rainfall. Their versatility and reliability position them as a preferred choice, offering a sturdy and weather-resistant solution for a range of architectural applications.

An additional advantage lies in the ease of maintenance, as these tiles can be replaced individually when broken, eliminating the need for replacing the entire roof. The straightforward installation process further contributes to its widespread adoption as a roofing material across the country.

The tested roofing panel consists of the following layers:
Outermost Layer: 12 mm thick Mangalore tiles
Timber purlins: 32 x18mm purlins of Teak wood
Timber Rafters: 32 x 45 mm purlins of Teak wood
Timber Stiffeners: 32 x18mm purlins of Teak wood
Innermost Layer: 32 x 45mm Teak wood rafters

Use: Mangalore tiles have garnered widespread popularity for residential roofing, particularly in tropical or coastal climates.

Figure 17: : Project of a house in Bangalore by Good Earth using Timber structure with Mangalore tiles roofing

Source: https://goodearth.org.in/connect/materials/benefits-of-clay-roof-tiles/

Assembly thickness: 93 mm | U-Value: 1.505 W/m^{2}K

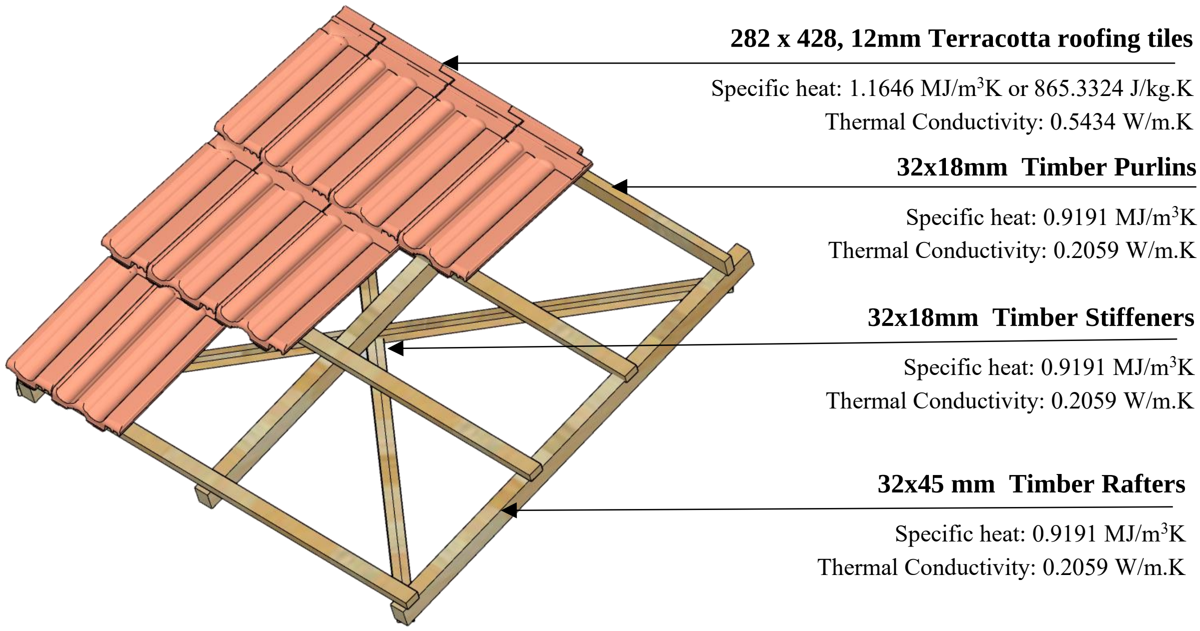


Figure 18: Illustration of Timber with Single sided Mangalore tile roofing sample used as the specimen for the test

Figure 19: Photographs showing Front (left) and the back (right) of the Timber with Single sided Mangalore tile roofing within the GHB apparatus

5. Timber + Double sided Mangalore tile roofing

This roofing assembly features a unique design, incorporating two layers of Mangalore tiles. Unlike conventional assemblies, this design includes one layer positioned conventionally on the top, while an additional layer is installed beneath, serving a dual purpose as both a structural component and a false ceiling. The crucial element of this innovative design lies in the air gap between the two layers of Mangalore tiles, creating an effective insulating barrier. This dual-layered system not only enhances the structural integrity of the roof but also contributes to improved thermal insulation, making it a sophisticated and efficient solution for roofing applications.

The tested roofing panel consists of the following layers:
Outermost Layer: 282 x 428 mm, 12mm thick Mangalore tiles
Timber purlins: 32 x18mm purlins of teak wood
Air gap: 21mm
Flat Mangalore tiles: 282 x 428 mm, 12mm thick
Timber rafters: 32 x 45mm teak wood rafters
Innermost Layer: 32 x18mm purlins of teak wood

Use: This assembly is commonly seen in residences, schools, churches in the hot and humid regions of the country

Figure 20: Roof construction using Timber structure with Double-sided Mangalore tiles roofing

Source: https://m.youtube.com/watch?v=so-bvHB9rSk

Assembly thickness: 105 mm | U-Value: 1.117 W/m²K

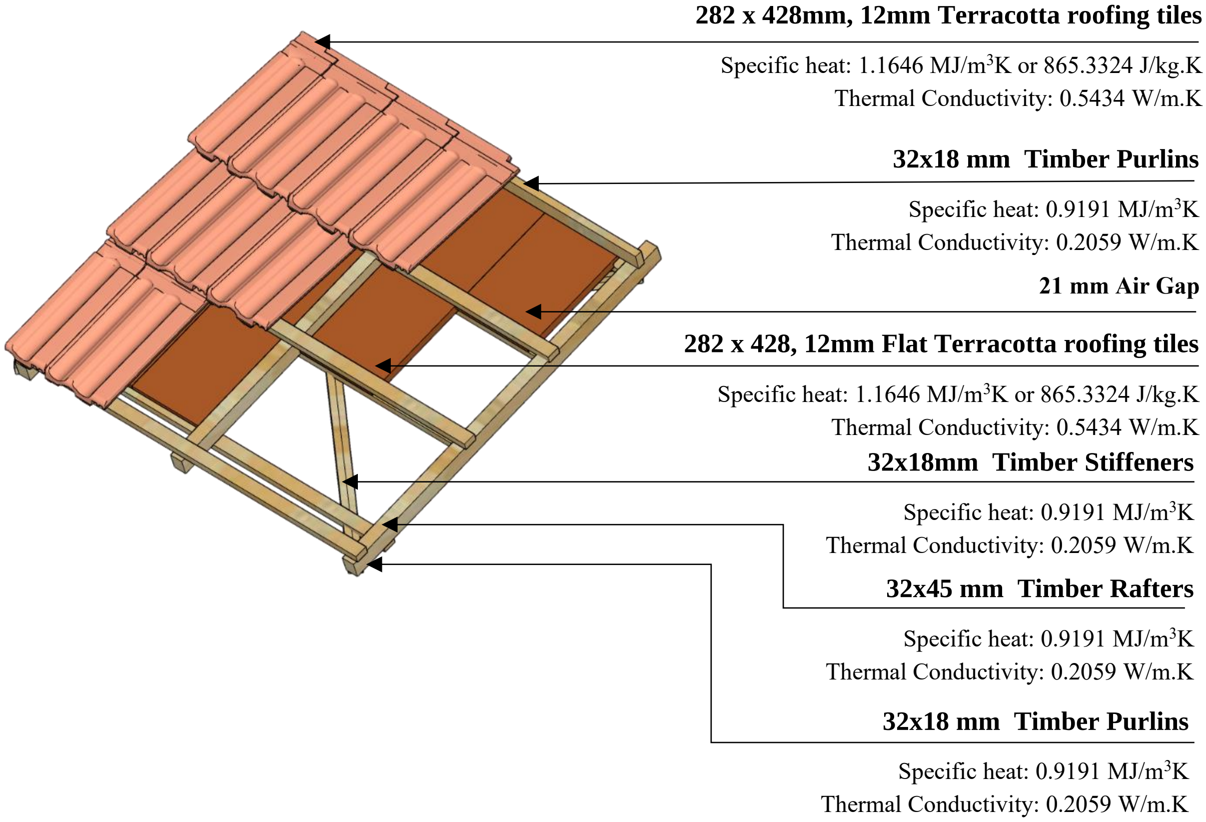


Figure 21: Illustration of Timber with Double sided Mangalore tile roofing sample used as the specimen for the test

Figure 22: Photographs showing the Front (left) and the back (right) of Timber structure with Double sided Mangalore tiles roofing within the GHB Apparatus

6. Bamboo + Single-sided Mangalore tile roofing

The assembly typically composed of timber and Mangalore tiles can seamlessly incorporate bamboo as a substitute for timber, offering a practical alternative, especially in regions where acquiring timber poses challenges. Bamboo proves to be a fitting replacement due to its ready availability in comparable section sizes and its impressive combination of durability, tensile strength, and compressive strength, allowing it to bear substantial loads.

The tested roofing panel consists of the following layers:
Outermost Layer: 12 mm thick Mangalore tiles
Timber purlins: 32 x18mm purlins of teak wood
Bamboo rafters: 60 mm Diameter Bamboo rafters
Innermost Layer: 32 x18 mm stiffeners of teak wood

Use: This particular assembly is also used in the construction of roofs of houses in regions where timber is difficult to get.

Figure 23: Roof construction using Bamboo structure with Clay tiles roofing

Source: https://bamboou.com/how-to-install-a-clay-tile-roof/0-cover-how-to-install-a-clay-tile-roof-for-a-bamboo-building/

Assembly thickness: 108 mm | U-Value: 1.502 W/m²K

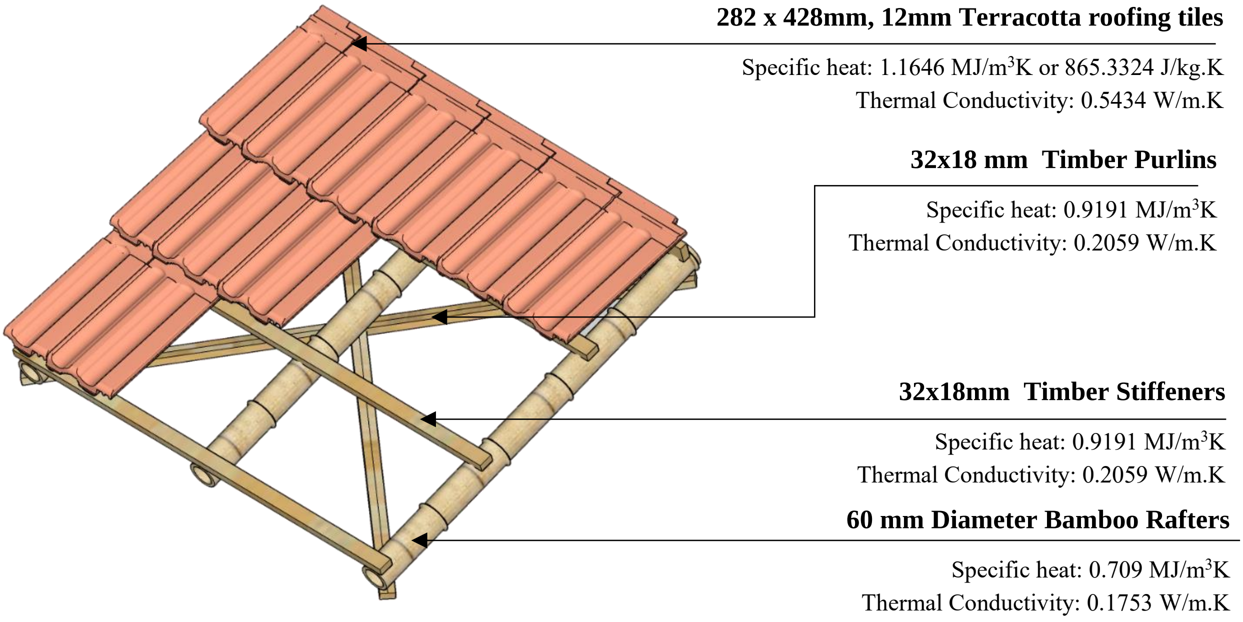


Figure 24: Illustration of Bamboo with Single sided Mangalore tile roofing sample used as the specimen for the test

Figure 25: Photographs showing Front (left) and the back (right) of the Bamboo with Single sided Mangalore tile roofing within the GHB Apparatus

7. Bamboo + Double-sided Mangalore tile roofing

Similar to the timber with double-sided Mangalore tiles roofing, this assembly simply replaces the timber with bamboo counterparts. In areas where timber scarcity is a concern, the easy adaptability of bamboo becomes a significant advantage. Its robust structural properties make it a reliable choice for maintaining the integrity of the assembly. This substitution not only addresses the issue of timber availability but also aligns with sustainable and eco-friendly construction practices, given bamboo's renewable and fast-growing nature. Consequently, this adaptable and resource-efficient modification ensures the continued feasibility and resilience of the timber and Mangalore tile assembly.

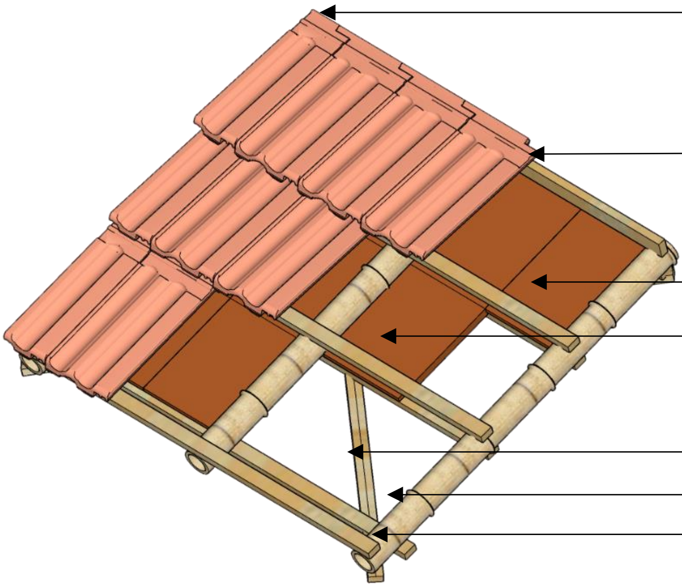
The tested roofing panel consists of the following layers:
Outermost Layer: 282 x 428 mm, 12mm thick Mangalore tiles
Timber purlins: 32x18mm purlins of teak wood
Air gap: 21mm
Flat Mangalore tiles: 282 x 428 mm, 12mm thick
Bamboo rafters: 60 mm Diameter Bamboo rafters
Innermost Layer: 32x18 mm stiffeners of teak wood

Use: Similar to the previous assembly, this roofing assembly is used for the constuction of houses in the regions where timber is difficult to get.

Figure 26: Roof consruction with double sided mangalore tiles roofing

Source: *https://m.youtube.com/watch?v=so-bvHB9rSk*

Assembly thickness: 114 mm | U-Value: 1.122 W/m^{2}K



282 x 428mm, 12mm Terracotta roofing tiles
Specific heat: 1.1646 MJ/m^{3}K or 865.3324 J/kg.K
Thermal Conductivity: 0.5434 W/m.K

32x18 mm Timber Purlins
Specific heat: 0.9191 MJ/m^{3}K
Thermal Conductivity: 0.2059 W/m.K

21 mm Air Gap

282 x 428, 12mm Flat Terracotta roofing tiles
Specific heat: 1.1646 MJ/m^{3}K or 865.3324 J/kg.K
Thermal Conductivity: 0.5434 W/m.K

32x18mm Timber Stiffeners
Specific heat: 0.9191 MJ/m^{3}K
Thermal Conductivity: 0.2059 W/m.K

60mm Diameter Bamboo Rafters
Specific heat: 0.709 MJ/m^{3}K
Thermal Conductivity: 0.1753 W/m.K

32x18 mm Timber Purlins
Specific heat: 0.9191 MJ/m^{3}K
Thermal Conductivity: 0.2059 W/m.K

Figure 27: Photographs showing Front (left) and the back (right) of the Bamboo with double-sided Mangalore tile roofing within the GHB Apparatus

8. Thatch roofing

Thatch roofing, a prevalent choice for rural dwellings in India, is crafted from dried hay sourced from maize or millet crops after the harvest season. This eco-friendly roofing material, known for its exceptional insulating qualities, is not only readily available but also contributes to sustainable construction practices.

The construction of a thatch roof typically involves layering and securing bundles of dried hay in an overlapping fashion. A sturdy framework, often made from bamboo or timber, supports the thatch bundles. The layers of hay create a dense and effective barrier against external elements while allowing for optimal ventilation. Additionally, a well-constructed thatch roof can withstand varying weather conditions, providing reliable shelter to occupants.

The tested roofing panel consists of the following layers:
Outermost Layer: 150 mm thick layer of Thatch
Timber purlins: 32 x18mm purlins of teak wood
Bamboo rafters: 60 mm Diameter Bamboo rafters
Innermost Layer: 32x18 mm stiffeners of teak wood

Use: Thatch roof is majorly used as a DIY material to construct houses in the rural regions. Some moderns buildings have also used thatch roof like the example shown below.

Figure 28: Roof construction of a restaurant using Thatch roof

Source: https://www.archdaily.com/900248/bamboo-long-house-restaurant-bambubuild/5b73f291f197ccf52700026e-bamboo-long-house-restaurant-bambubuild-photo

Assembly thickness: 246 mm | U-Value: 0.234 W/m²K

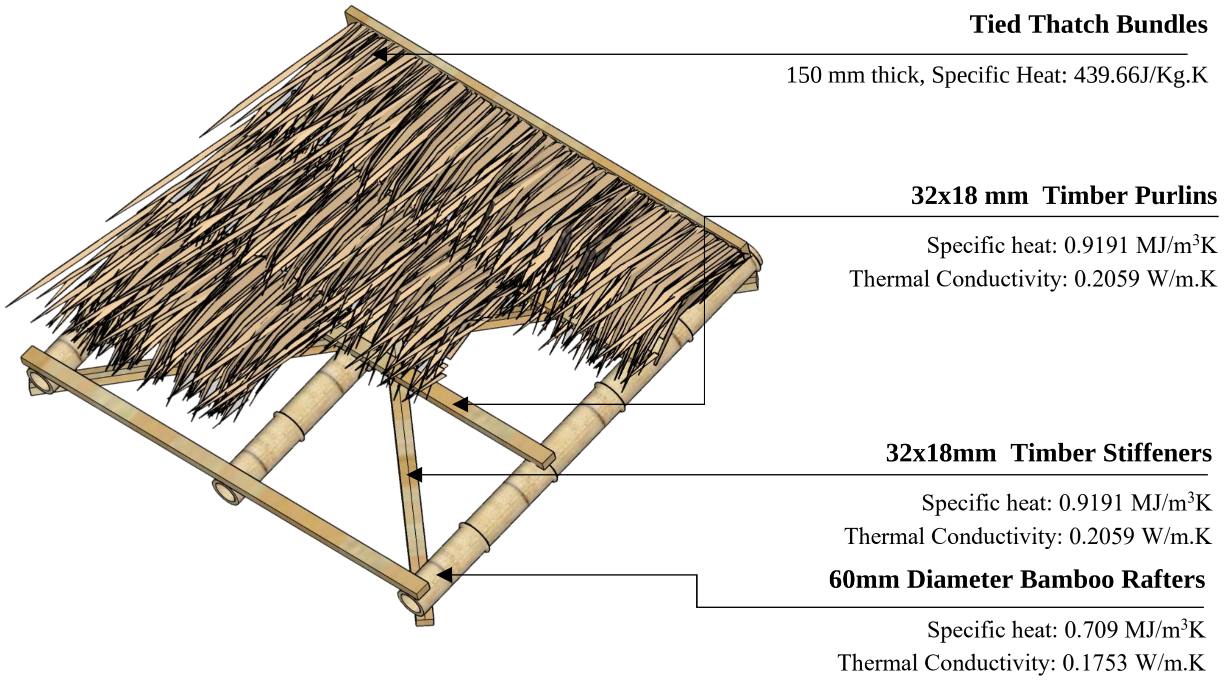


Figure 29: Illustration of Thatch roofing sample used as the specimen for the test

Figure 30: Photographs showing Front (left) and the back (right) of the Thatch roofing within the GHB Apparatus

9. Thatch roofing with XPS Insulation

Thatch roof construction, a traditional technique, combines natural aesthetics with modern insulation like XPS (Extruded Polystyrene). Typically, thatch comprises dried hay layered on a timber, bamboo or metal roof frame. Integrating XPS insulation enhances energy efficiency by offering thermal resistance, minimizing heat transfer and maintaining interior comfort. The XPS insulation also provides durability, resisting moisture and mold growth, prolonging the roof's lifespan offering sustainable and comfortable shelter solutions.

The tested roofing panel consists of the following layers:
Outermost Layer: 150 mm thick layer of Thatch
Timber purlins: 32x18mm purlins of teak wood
Bamboo Rafters: 60mm Diameter Bamboo
Innermost Layer: 75mm Thick XPS Layer

Use: Majorly used in residential buildings, schools etc.

Figure 31: Roof construction of mud house using thatch in Alwar, Rajasthan

Source: https://www.archdaily.com/989711/mud-house-sketch-design-studio/63344dc44dba6e02cc399a6a-mud-house-sketch-design-studio-photo

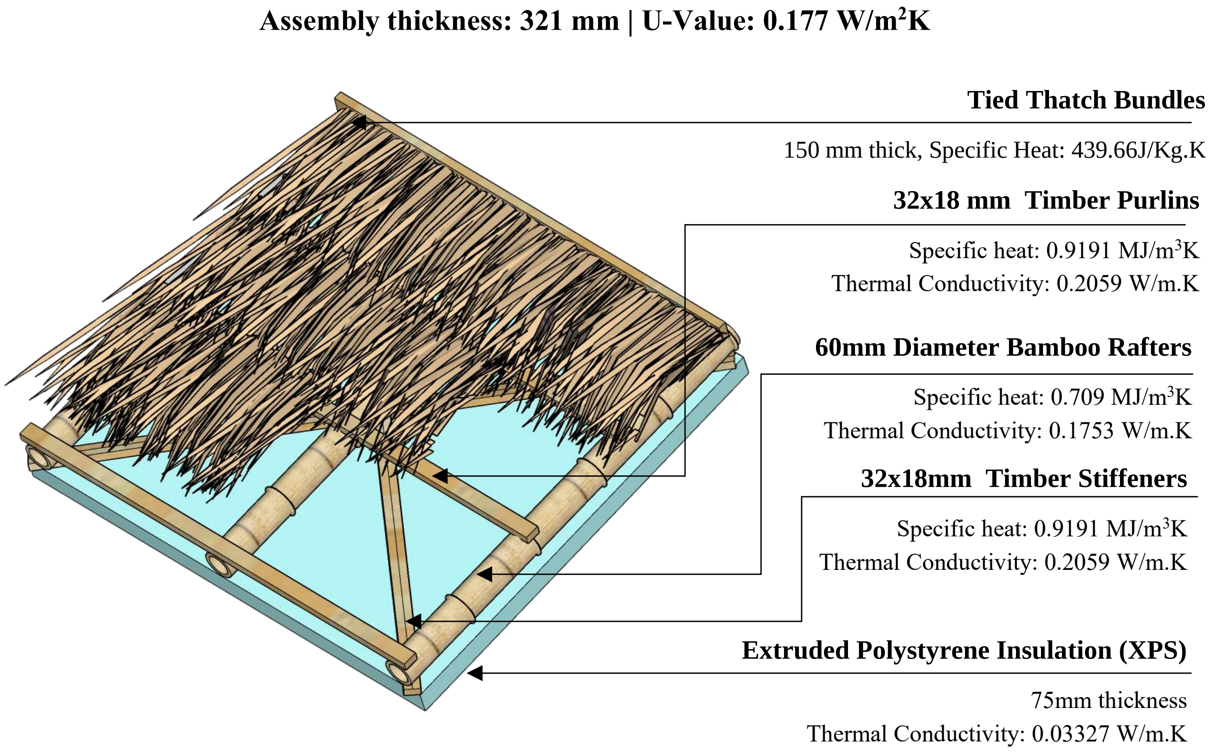


Figure 32: Illustration of Thatch roofing with 75mm XPS sample used as the specimen for the test

Figure 33: Photographs showing Front (left) and the back (right) of the Thatch roofing within the GHB Apparatus.

10. Timber + Single sided Mangalore tile roofing with Cement Fiber Board

Timber with single sided mangalore tile roofing can be constructed with a several variations like cement fiber board, insulations, etc. We chose this particular variation since its use is widespread and it is easy to construct. This variation involves using cement fiber boards as an underlayment beneath the Mangalore tiles. CFB provides a solid and durable surface for the tiles to rest upon. It enhances the structural integrity of the roof, improves weather resistance, and helps prevent water seepage. Additionally, CFB is resistant to fire, pests, and rot, further increasing the longevity of the roof.

The tested roofing panel consists of the following layers:
Outermost Layer: 200 mm thick layer of Thatch
Timber purlins: 32 x18mm purlins of teak wood
Bamboo Rafters: 60 mm Diameter Bamboo
Innermost Layer: 12 mm thick Cement Fiber sheet

Use: Widespread use in residential buildings

Figure 34: Roof construction using timber with single sided mangalore tile roofing and cement sheet

Source: https://www.ecopro.co.in/fibre-cement-roofs-a-growing-trend-in-india/

Assembly thickness: 105 mm | U-Value: 1.484 W/m²K

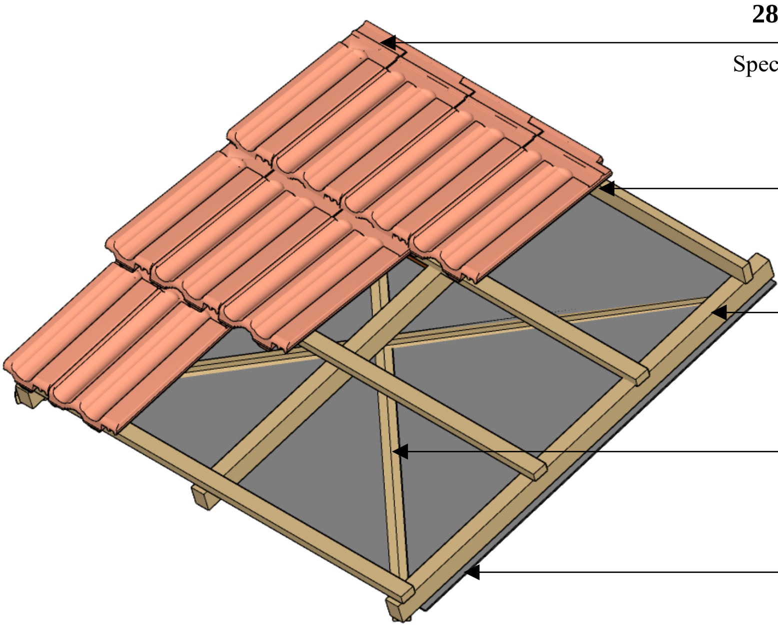


Figure 35: Illustration of sample used as the specimen for the test

Figure 36: Photographs showing Front (left) and the back (right) of the timber with single sided mangalore tiles with cement board within the GHB Apparatus

Annexure II: Schematic Drawings of the Test Samples

This section elaborates on the testing details of the chosen roofing assemblies.

1. Flat Pre-Painted Galvanized Iron sheet with PUF Insulation

Total Assembly thickness: 121.4 mm
U-Value: 0.253 W/m^{2}K

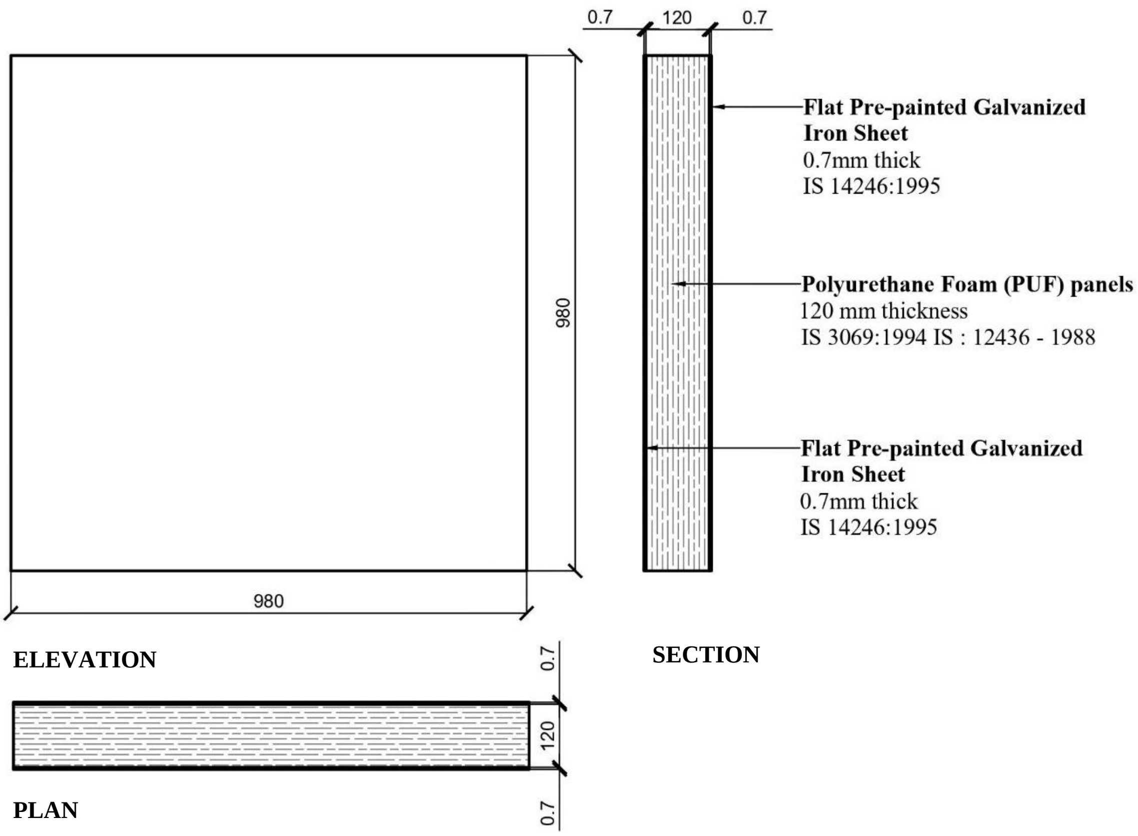


Figure 37:Schematic drawings of Flat PPGI sheet with PUF insulation as per specifications

Table 4: Roofing technology and testing details for Flat PPGI sheet with PUF Insulation roofing assembly

Particulars	Specification	Thickness (mm)	Testing Standard	Properties		
				Thermal Conductivity W/m.K	Specific Heat Per unit mass (J/kg.K)	Specific Heat Per unit \volume (MJ/m^{3}K)
Flat PPGI Sheet	IS 14246:1995	0.7	-	-	-	-
PUF Insulation	IS 3069:1994 IS : 12436 - 1988	120	ASTM C518	0.02901	-	0.0413
Flat PPGI Sheet	IS 14246:1995	0.7	-	-	-	-

2. Curved Pre-Painted Galvanized Iron sheet with PUF Insulation

Total Assembly thickness: 121.4 mm
U-Value: 0.246 W/m^{2}K

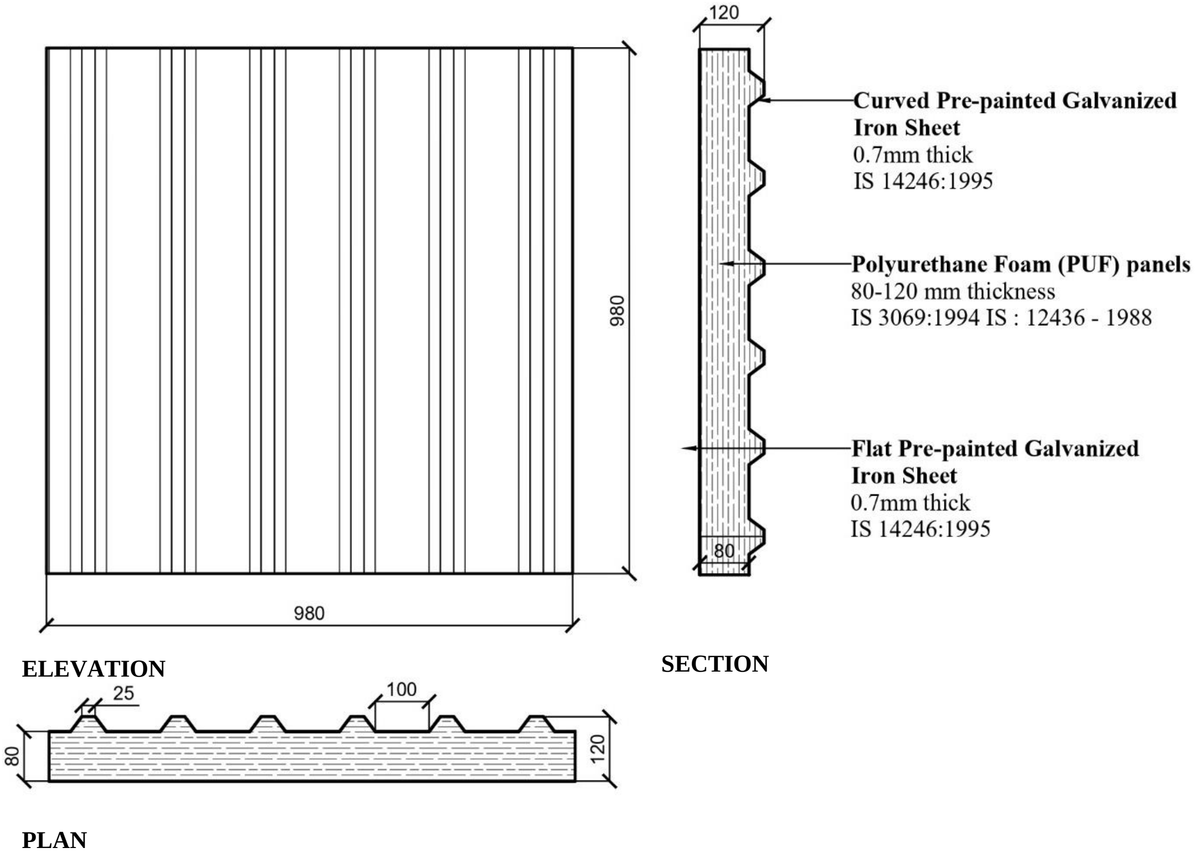


Figure 38:Schematic drawings of Curved PPGI sheet with PUF insulation as per specifications

Table 5: Roofing technology and testing details for Curved PPGI sheet with PUF insulation roofing assembly

Particulars	Specification	Thickness (mm)	Testing Standard	Properties		
				Thermal Conductivity (W/m.K)	Specific Heat Per unit mass (J/kg.K)	Specific Heat Per unit volume (MJ/m^{3}K)
Curved PPGI Sheet	IS 14246:1995	0.7	-	-	-	-
PUF Insulation	IS 3069:1994 IS : 12436 - 1988	80-120	ASTM C518	0.02901	-	0.0413
Flat PPGI Sheet	IS 14246:1995	0.7	-	-	-	-

3. TRIMDEK single skin steel sheet with PUF insulation and Aluminium sheet water proofing

Total Assembly thickness: 76.2 mm
U-Value: 0.255 W/m^{2}K

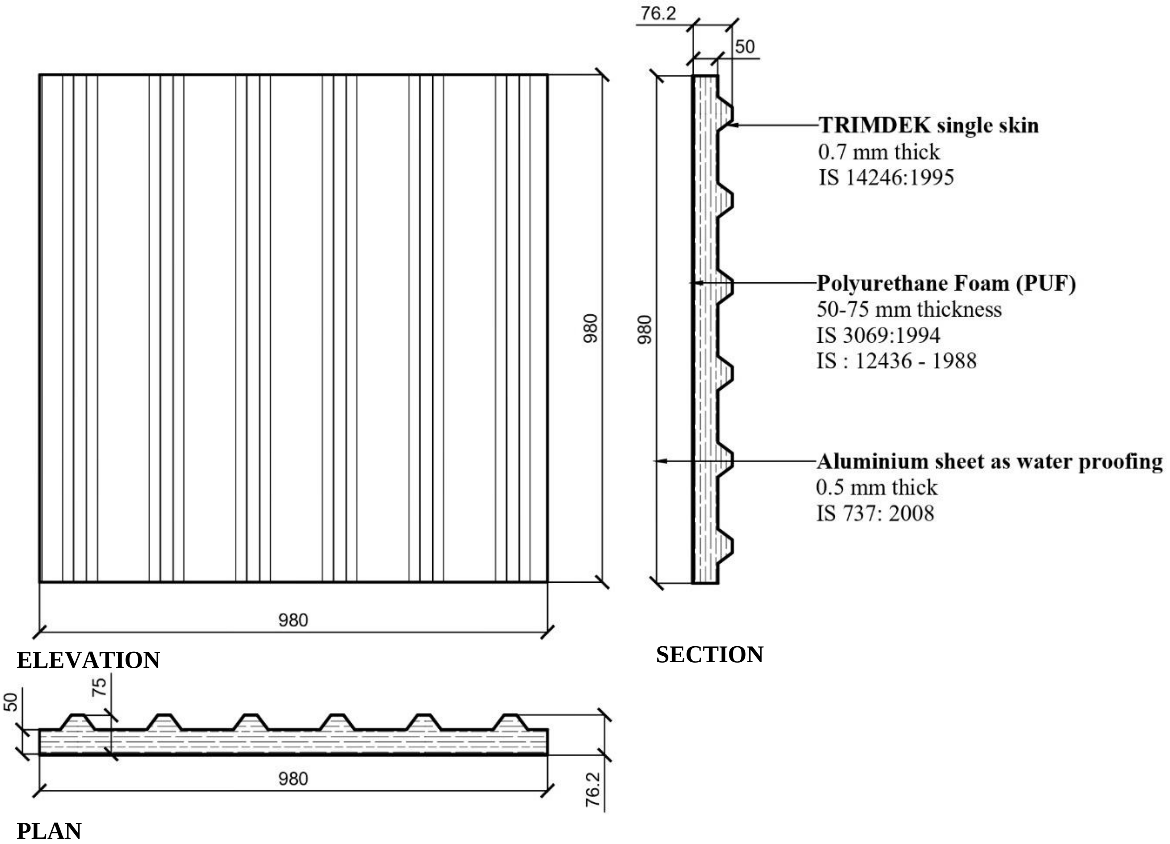


Figure 39:Schematic drawings of TRIMDEK single skin steel with PUF insulation and Aluminium sheet water proofing as per specifications

Table 6:Roofing technology and testing details for TRIMDEK single skin steel sheet with PUF insulation and Aluminium sheet water proofing roofing assembly

Particulars	Specification	Thickness (mm)	Testing Standard	Properties		
				Thermal Conductivity (W/m.K)	Specific Heat Per unit mass (J/kg.K)	Specific Heat Per unit volume (MJ/m^{3}K)
Curved PPGI Sheet	IS 14246:1995	0.7	-	-	-	-
PUF Insulation	IS 3069:1994 IS : 12436 - 1988	50-75	ASTM C518	0.02901	-	0.0413
Aluminium sheet	IS 14246:1995	0.5	-	-	-	-

4. Timber with single-sided Mangalore tiles roof

Total Assembly thickness: 93 mm
U-Value: 1.505 W/m^2K

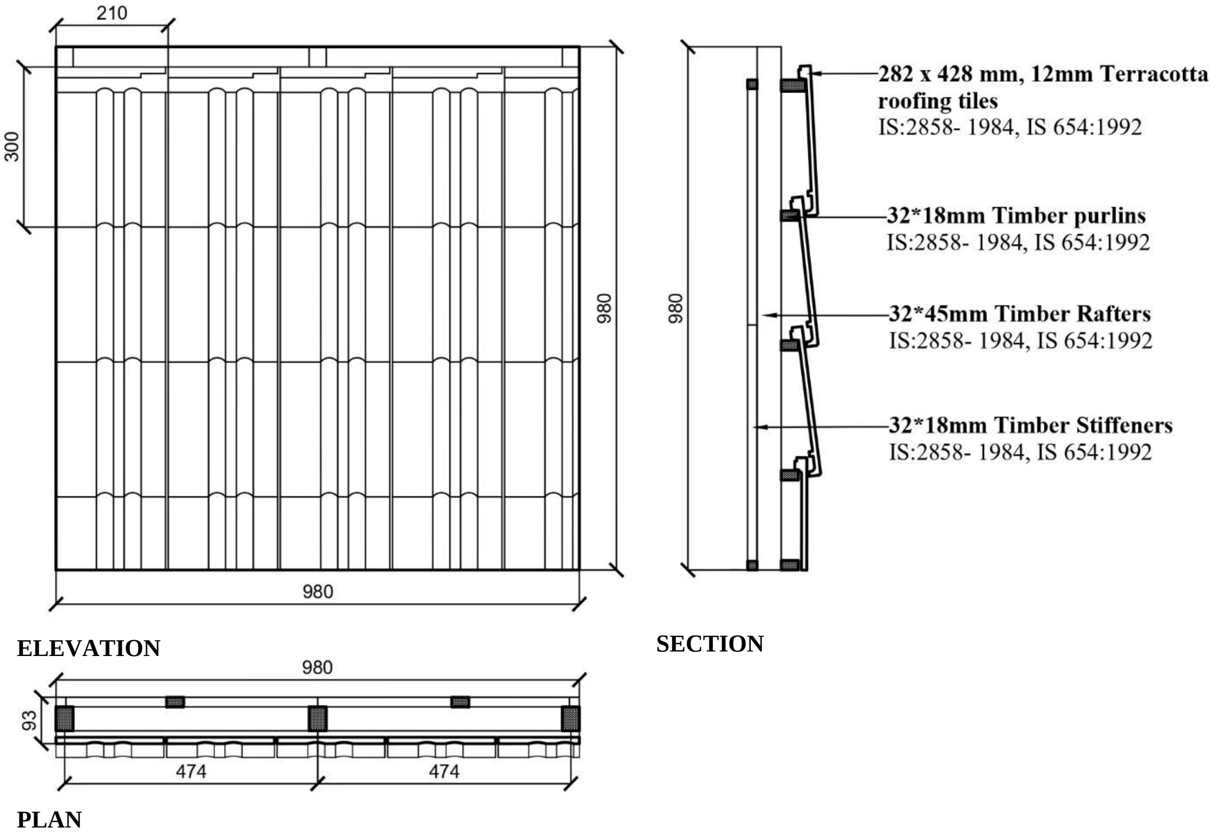


Figure 40: Schematic drawings of timber with single sided Mangalore tiles roof as per specifications

Table 7:Roofing technology and testing details for Timber with single sided Mangalore tiles roof assembly

Particulars	Specification	Thickness (mm)	Testing Standard	Properties		
				Thermal Conductivity (W/m.K)	Specific Heat Per unit mass (J/kg.K)	Specific Heat Per unit volume (MJ/m3K)
Mangalore Tiles	IS:2858- 1984 IS 654:1992	12	ISO 22007-2	0.5434	865.3324	1.1646
Timber Purlins		18		0.2059	-	0.9191
Timber Rafters		45		0.2059	-	0.9191

5. Timber with double-sided mangalore tiles roof

Total Assembly thickness: 105 mm
U-Value: 1.117 W/m^{2}K

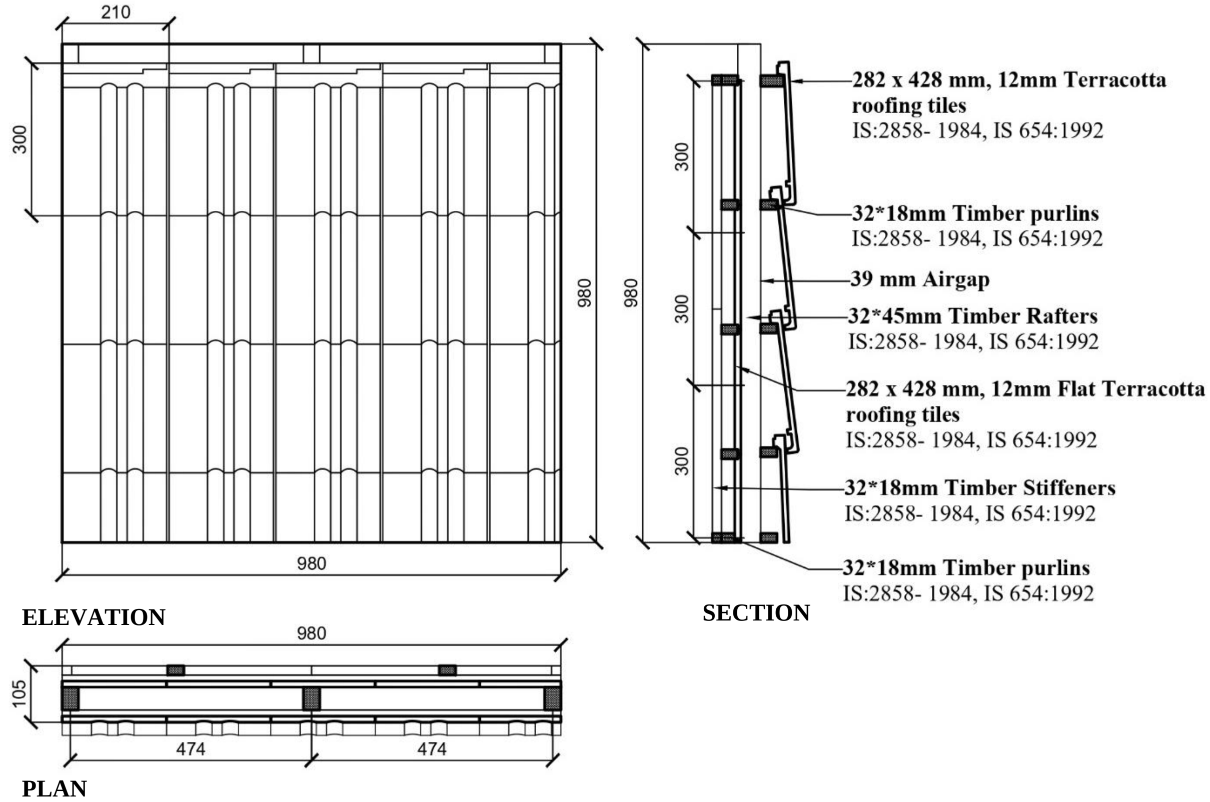


Figure 41:Schematic drawings of Timber with double sided Mangalore tiles roof as per specifications

Table 8:Roofing technology and testing details for Timber with double sided Mangalore tiles roof assembly

Particulars	Specification	Thickness (mm)	Testing Standard	Properties		
				Thermal Conductivity (W/m.K)	Specific Heat Per unit mass (J/kg.K)	Specific Heat Per unit volume (MJ/m^{3}K)
Mangalore tiles	IS:2858- 1984 IS 654:1992	12	ISO 22007-2	0.5434	865.3324	1.1646
Timber Purlins		18	ISO 22007-2	0.2059	-	0.9191
Airgap		21	-	-	-	-
Mangalore tiles		12	ISO 22007-2	1.0567	848.3257	2.2004
Timber Rafters		45	ISO 22007-2	0.2059	-	0.9191

6. Bamboo with single sided Mangalore tiles

Total Assembly thickness: 108 mm
U-Value: 1.502 W/m^{2}K

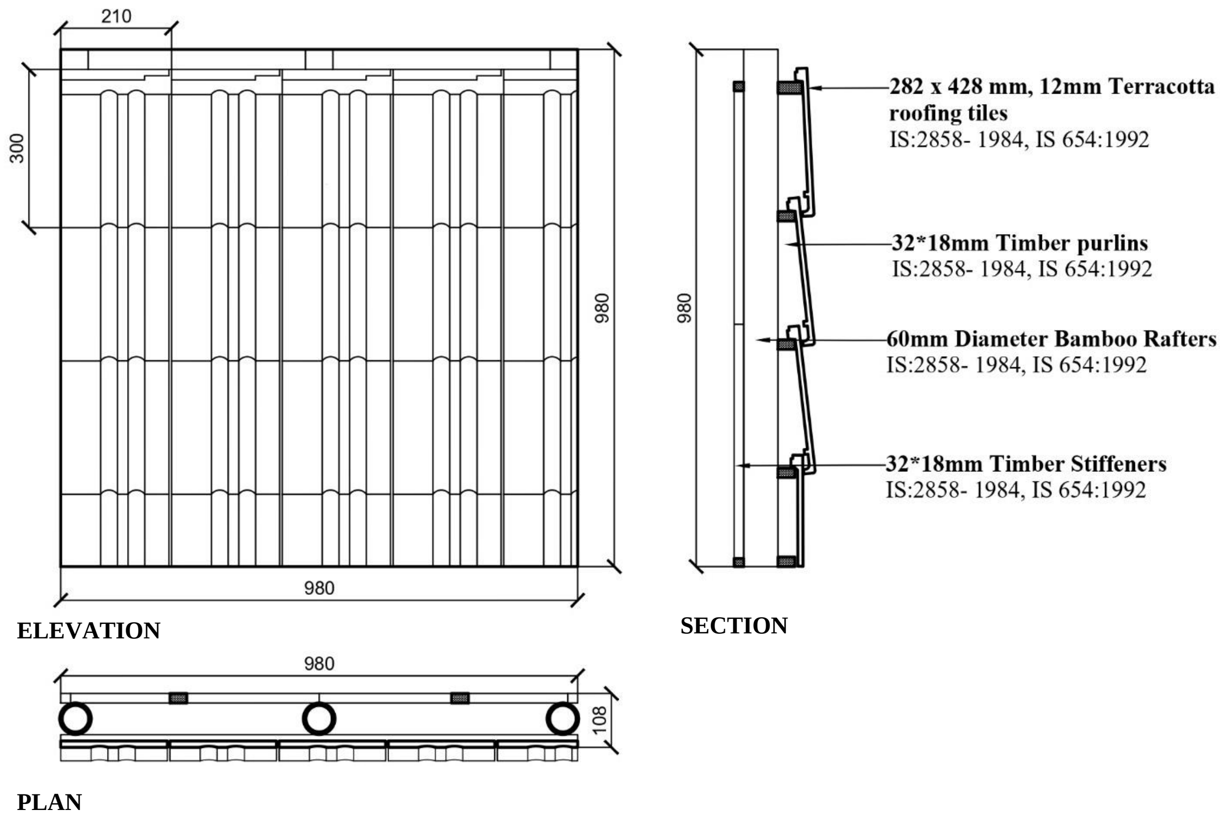


Figure 42:Schematic drawings of Bamboo with single sided Mangalore tiles roof as per specifications

Table 9:Roofing technology and testing details for Bamboo with single sided Mangalore tiles roof assembly

Particulars	Specification	Thickness (mm)	Testing Standard	Properties		
				Thermal Conductivity (W/m.K)	Specific Heat Per unit mass (J/kg.K)	Specific Heat Per unit volume (MJ/m^{3}K)
Mangalore Tiles	IS:2858- 1984 IS 654:1992	12	ISO 22007-2	0.5434	865.3324	1.1646
Timber Purlins		18		0.2059	-	0.9191
Bamboo Rafters		60mm Dia CC 490mm		0.1753	-	0.709

7. Bamboo with Double sided Mangalore tiles

Total Assembly thickness: 114 mm

U-Value: 1.122 W/m^{2}K

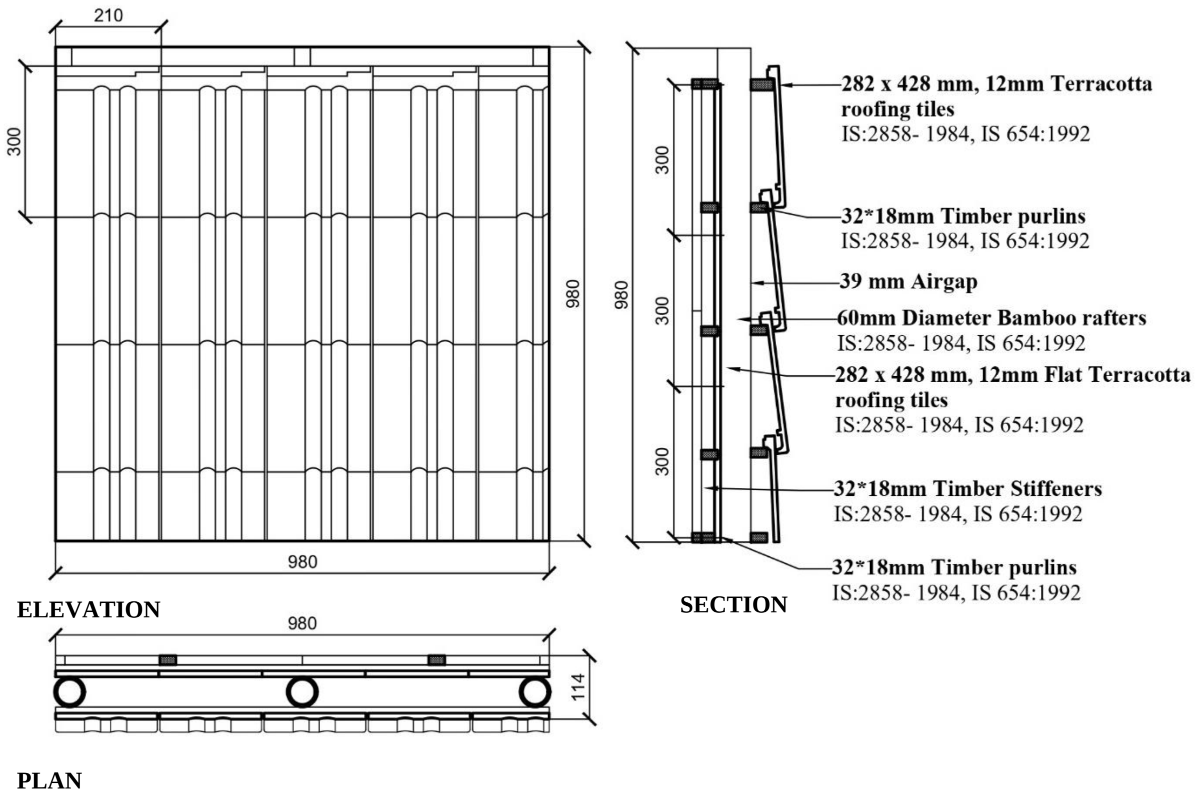


Figure 43:Schematic drawings of Bamboo with Double sided Mangalore tiles roof as per specifications

Table 10:Roofing technology and testing details for Bamboo with Double sided Mangalore tiles roofing assembly

Particulars	Specification	Thickness (mm)	Testing Standard	Properties		
				Thermal Conductivity (W/m.K)	Specific Heat Per unit mass (J/kg.K)	Specific Heat Per unit volume (MJ/m^{3}K)
Mangalore tiles	IS:2858- 1984 IS 654:1992	12	ISO 22007-2	0.5434	865.3324	1.1646
Timber Purlins		18	ISO 22007-2	0.2059	-	0.9191
Airgap		21	-	-	-	-
Flat Mangalore tiles		12	ISO 22007-2	1.0567	848.3257	2.2004
Bamboo Rafters		60mm Dia CC 490mm	ISO 22007-2	0.1753	-	0.709

8. Thatch roof

Total Assembly thickness: 246 mm
U-Value: 0.234 w/m^{2}K

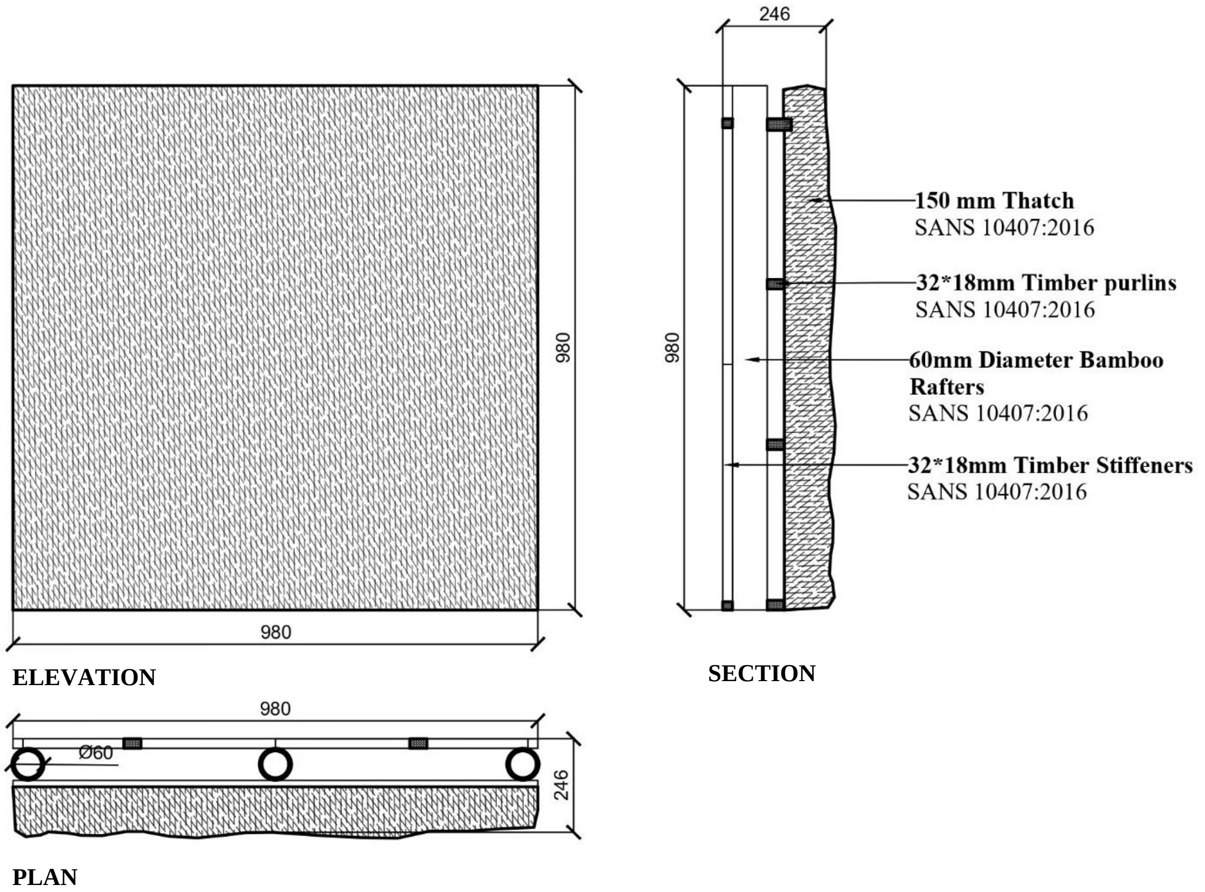


Figure 44:Schematic drawings of Thatch roof as per specifications

Table 11:Roofing technology and testing details for Thatch roof assembly

Particulars	Specification	Thickness (mm)	Testing Standard	Properties		
				Thermal Conductivity (W/m.K)	Specific Heat Per unit mass (J/kg.K)	Specific Heat Per unit volume (MJ/m^{3}K)
Thatch	SANS 0407:2016	150	ISO 22007-2	-	439.66	-
Timber Purlins		18	ISO 22007-2	0.2059	-	0.9191
Bamboo Rafters		60mm Dia CC 490mm	ISO 22007-2	0.1753	-	0.709

9. Thatch roof with 75mm XPS insulation

Total Assembly thickness: 321 mm
U-Value: 0.177 W/m^{2}K

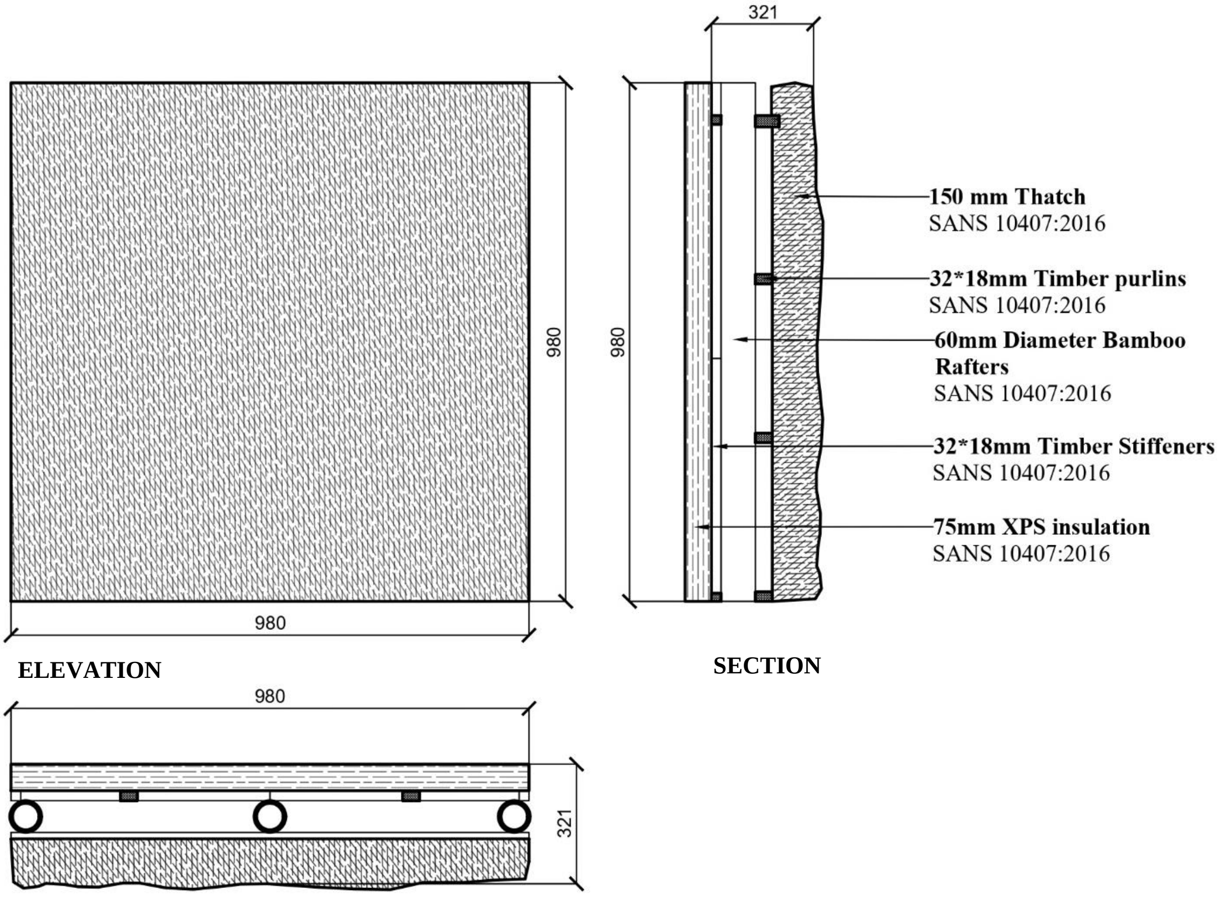


Figure 45:Schematic drawings of Thatch roof with 75mm XPS insulation as per specifications

Table 12:Roofing technology and testing details for Bamboo with Double sided Mangalore tiles roofing assembly

Particulars	Specification	Thickness (mm)	Testing Standard	Properties		
				Thermal Conductivity (W/m.K)	Specific Heat Per unit mass (J/kg.K)	Specific Heat Per unit volume (MJ/m^{3}K)
Thatch	SANS 0407:2016	150	ISO 22007-2	-	439.66	-
Timber Purlins		18	ISO 22007-2	0.2059	-	0.9191
Bamboo Rafters		60mm Dia CC 490mm	ISO 22007-2	0.1753	-	0.709
XPS Insulation	ASTM C578 - 19	75	ASTM C518	0.03327	-	-

10. Timber with single sided Mangalore tile roof and cement Board

Total Assembly thickness: 105 mm

U-Value: 1.484 W/m^{2}K

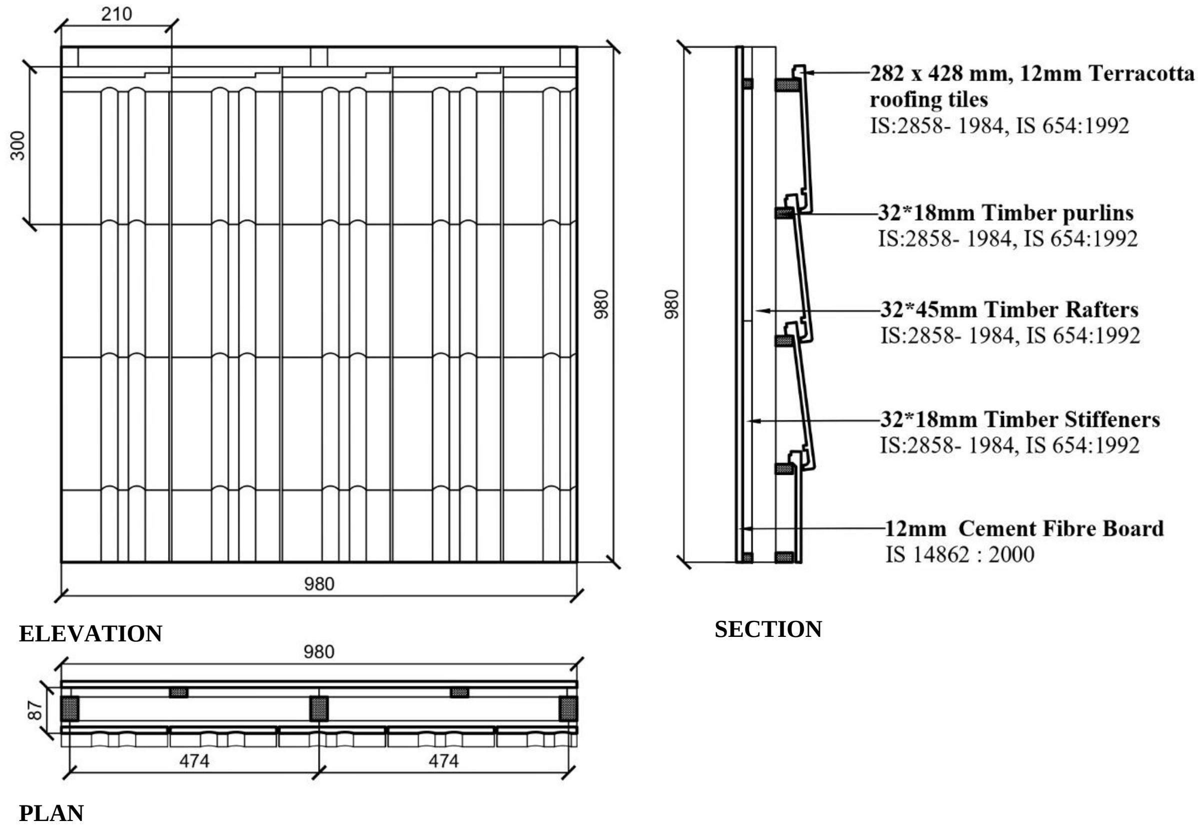


Figure 46:Schematic drawings of Timber with single sided Mangalore tile roof and cement board roof as per specifications

Table 13: Roofing technology and testing details for Timber with single sided Mangalore tile roof and cement board roof assembly

Particulars	Specification	Thickness (mm)	Testing Standard	Properties		
				Thermal Conductivity (W/m.K)	Specific Heat Per unit mass (J/kg.K)	Specific Heat Per unit volume (MJ/m^{3}K)
Mangalore Tiles	IS:2858- 1984 IS 654:1992	12	ISO 22007-2	0.5434	865.3324	1.1646
Timber Purlins		18		0.2059	-	0.9191
Timber Rafters		45		0.2059	-	0.9191
Cement Fiber Board	IS 14862 : 2000	12		0.5128	-	1.1073

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ISO 22007-2 : Plastics — Determination of thermal conductivity and thermal diffusivity —Part 2 : Transient plane heat source (hot disc) method. Edition 2022-06

C518 − 21 Standard Test Method for Steady-State Thermal Transmission Properties by Means of the Heat Flow Meter Apparatus, Published September 2021. DOI: 10.1520/C0518-21

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U.S.- India Joint Center for Building Energy Research and Development (CBERD)

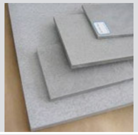
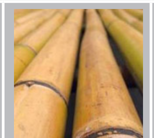
and

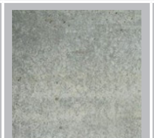
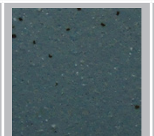
Ministry of New and Renewable Energy (MNRE)

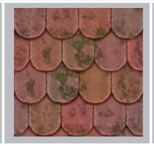
Thermo-Physical Properties

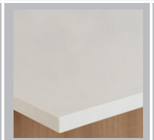
of

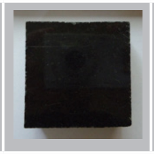
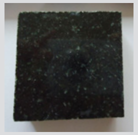
Construction Materials

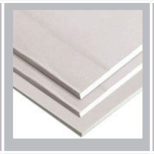
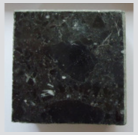
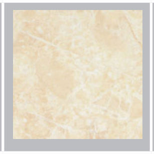
Name	Form	Density kg/m^3	Thermal Conductivity W/(mK)	Specific Heat MJ/m^3K	Image	Description
Acrylic Sheet	Board	1145	0.2174	1.5839		Acrylic sheet has unique physical characteristics. It is much clear, more impact resistant and weighs half as compared to finest optical glass. It doesn't turn yellow after a while, has 92 % light transmittance and is an excellent insulator. It is available in number of translucent as well as transparent colours.
Armor	Insulation	270	0.0678	0.1578		Armor is a class – A building product made up of very high quality natural cotton fibres. It is eco-friendly and carries high resistance values in case of smoke, fungi, fire and corrosiveness.
Asbestos Cement Board	Board	1404	0.4709	0.7218		Asbestos cement board contains high proportion of asbestos sheet which are bonded together with Portland cement. It is a dense rigid board which is resistant to flame, weathering and fire and doesn't allow easy heat flow. It is mostly used in board form in buildings.
Asbestos Sheet -Shera	Board	1377	0.5128	1.2043		Asbestos sheet is made up of very high quality of asbestos fibres. It is very durable, fire resistant and very efficient insulating material. It is used in form of sheet. Asbestos cause's health risks therefore the use of it nowadays has gone minimal.
Autodaved Aerated Concrete Block (AAC)	Block	642	0.1839	0.7940		AAC is a porous, lightweight, resource efficient concrete used as precast building material providing structure, insulation, and fire and mould resistance. Its improved thermal efficiency helps in reducing building heating and cooling load. AAC is manufactured by mixing a silica rich material such as fine ground sand or fly ash, cement, a sulphate source such as gypsum, quicklime, a rising agent and water. Workability allows accurate cutting and easy installation thus minimizing generation of solid waste. AAC products include blocks, wall panels, floor and roof panels, and lintels.
Bamboo	Wood	913	0.1959	0.6351		Bamboo is type of plant with hard hollow stem. It is woody in nature and has an extremely hard surface. Before application it needs to be chemically treated. It is considered as one of the best renewable resources available on earth. Apart from its other structural non-structural uses it is also used as reinforcement these days.
Brass	Metal	8500	106.4800	11.1164		Brass has muted yellow colour and higher malleability in comparison to bronze and zinc. The relatively low melting point of brass and its flow characteristics makes it a relatively easy material to cast. Its cost effectiveness, low manufacturing, corrosion resistance and machinability allow manufacturers to produce vast range of products. It is mostly used in Commercial plumbing and OEM applications also its antibacterial properties make it useful for doorknobs especially in hospitals.
Calcium Silicate Board	Board	1016	0.2810	0.8637		Calcium silicate board is considered much safer and better option than asbestos cement board for providing insulation. It is used in construction industry as insulation and can also be used for equipment insulation.

Name	Form	Density kg/m³	Thermal Conductivity W/(mK)	Specific Heat MJ/m³K	Image	Description
Composite Marble	Stone	3146	2.4400	2.1398		Cement marble crust is composed of natural marble chips and powder with highly specialised polyester resin. It is generally formed in blocks of various sizes and can be cut and polished like natural marble. It has greater compactness; greater elasticity; is more durable and delivers greater colour uniformity as compared to natural marble. It is used for internal flooring, vanity and laundry tops etc.
Cement Board	Board	1340	0.4384	0.8113		A cement board is made up of cement and reinforcing fibres which are then formed into various sizes of board. It is mainly used as a backing board which adds strength and impact resistance to wall and is better in comparison to gypsum boards. Thin cement board sheets allows bending in case of curved surfaces.
Cement Bonded Particle Board	Board	1251	0.3275	1.1948		Cement Bonded Particle Board (CBPB) is dimensionally stable having superior structural integrity and does not delaminate in water. CBPB can be sanded, routed, drilled, sawn, planed, nailed and screwed with standard carpentry tools. The board is easy to maintain as it is highly scratch resistant and resistive towards pest. Available in various sizes and is applicable for False Ceiling, Wall Cladding, kitchen cabinets, Cupboards, Cabins, Partitions and Door panels.
Ceramic Fiber Blanket	Insulation	128	0.0491	0.1093		Ceramic fibre blanket is manufactured from high strength spun ceramic fibres. It is lightweight, thermally efficient, have excellent thermal stability, low shrinkage at elevated temperature, low heat storage, good cold strength, excellent hot strength, thermal shock resistance and excellent resistance to most chemicals. It is used as insulation in construction industry.
Cement Fiber Board	Board	1276	0.3880	0.8973		Cement fibre Board Panel is made up of cement, sand and recycled wood waste available at economic pricing. Fibre cement board is more durable and less toxic then vinyl and have less maintenance than wood. It is resistant to fire, insects, rot and general decay. Waterproof, fire resistant polymer texture coating is applied on exterior panels. It is used for roof panels, wall panels, false ceiling, door, window etc.
Cement Plaster		278	1.2080	0.9719		Cement plaster is mixture of suitable sand, portland cement and water which is normally applied to masonry interiors and exteriors to achieve a smooth surface.
Cement Powder	Powder	1070	0.1137	0.7943		Cement power is made by heating limestone and then grinding it to form fine powder. This powder when mixed with stone, sand and aggregate forms concrete. It is widely used in construction.
Ceramic Blue Tile	Tile	2707	1.3720	1.2082		Ceramic tile is made up of materials like porcelain and earthenware. It is extremely durable, has great strength. Cooling and heating systems can be installed underneath it. This particular tile is blue in colour and is available in many colours and sizes. It can be used in wide range of application like flooring, shower area, roofing, countertops and walls.

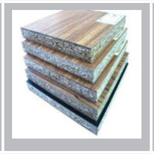
Name	Form	Density kg/m^3	Thermal Conductivity W/(mK)	Specific Heat MJ/m^3K	Image	Description
Ceramic Frit Glass	Glass	2520	0.6882	0.7859		Ceramic frit glass when combined with tinted, reflective or low e glass controls light transmittance, solar heat gain is reduced and performance of the space is enhanced. It is available is different colours and can be specified for exterior as well as interior but the surface needs to be protected from direct contact with environment.
Ceramic Tile - Bathroom	Tile	2549	0.8018	1.6168		Ceramic bathroom tile has great strength, is extremely durable and easy to maintain and is preferred for use at places where hygiene is a prime concern like bathroom. It is also anti-water absorption and easy to clean.
Ceramic Tile	Tile	2700	1.5996	1.1438		Ceramic tile is made up of materials like porcelain and earthenware. It is extremely durable, has great strength. Cooling and heating systems can be installed underneath it. It can be used in wide range of application like flooring, shower area, roofing, countertops and walls.
Chile Wood	Wood	362	0.1422	0.4102		Chile is a white or pale yellow soft wood mostly found in northern hemisphere. It is light in weight and straight grained. It is resistant to shrinking and swelling and is mostly used in packing materials.
Chitodio	Stone	3209	3.7512	2.1223		Chitodio stone is available in different design and colours and is mainly used as flooring of super market, shopping mall, warehouse flooring, etc.
Clay Tile	Tile	2531	0.6323	1.4253		Clay tile is made of rich earth which is known for its plasticity. It is used for number of application like roofing, flooring, wall cladding etc. and adds pleasing natural look to the place.
Float Glass/ Clear Glass	Glass	2477	1.0522	1.9654		Float glass is manufactured from common glass making raw materials where some additional refining agents are added to it to improve its properties. It can be tempered, bent, laminated and can also be decorated.
Concrete Block 25/50	Block	2427	1.3957	0.4751		Concrete Block 25/50 also called concrete masonry unit (CMU) is a precast concrete block. Most concrete block have one or more hollow cavities, and their sides may be cast smooth or with a design. It is widely used in construction industry for making walls.

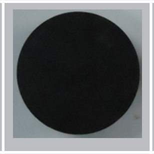
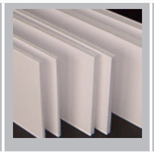
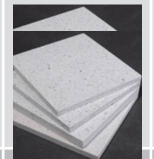
Name	Form	Density kg/m³	Thermal Conductivity W/(mK)	Specific Heat MJ/m³K	Image	Description
Concrete Block 30/60	Block	2349	1.4107	0.7013		Concrete Block 30/60 is better in terms of thermal properties than Concrete Block 25/50. It is also known as concrete masonry unit (CMU). Most concrete block have one or more hollow cavities, and their sides may be cast smooth or with a design. It is widely used in construction industry for making walls.
Corian	Board	1750	1.0120	2.0921		Corian is a solid, homogeneous, non-porous surfacing material composed of natural minerals and acrylic resin. It can be thermoformed by heating, allowing unique shapes to be created. It is very durable, hygienic, repairable, non-toxic, translucent, colourful, creates inconspicuous joints and is workable like hardwood. Corian solid surfaces deliver high performance and outstanding aesthetics. It can be used for wall cladding, kitchen countertops and bathroom vanity tops.
Crystal White Tile	Tile	2390	1.5094	1.9427		Crystal white tile is a man-made material having crystal, sparkly finish known for its strength and durability. Crystal tile is available in wide variety of colours, finished and sizes. Workability is easy but has to be laid with great precision. It can be customised as per client's requirement and adds different dimension to space when teamed with mosaics, border tiles, wood furnishing etc. It is widely used for bathrooms, kitchens, hallways flooring.
Dholpuri Stone	Stone	2262	3.0840	1.5830		Dholpur stone is a type of sandstone having good mechanical strength, low water absorption, saline water resistance, weather resistance and superior performance. It is available in various colours and sizes. It is used for interior as well as exterior application such as landscaping, stonewalls, roofing, flooring, cladding, pillars etc.
Distilled Water	Water	1000	0.6134	3.8165		Distilled water is composition of hydrogen and oxygen molecules and is widely used in construction projects.
Engineered Wood Floor Tiles	Tile	571	0.2527	1.4230		Engineered wood floor is composed of multiple layers of wood in form of plank that are cross layered, glues and pressed together. It is more resistant to higher moisture levels as compared to slid wood flooring thus are widely used in regions having higher relative humidity levels. Engineered wood is much more stable making it a universal product that can be installed over all types of subfloors.
Extruded Polystyrene XPS	Insulation	30	0.0321	0.0374		Extruded polystyrene (XPS) foam plastic insulation has a closed cell structure and lacks voids which make XPS very strong and durable material. It has low thermal conductivity and diffusivity. Its closed cell structure helps resist moisture penetration without even using a facer. It is available in variable compressive strength and is used for insulation in wall, roof, ceiling and building foundation.
Fiber Reinforced Plastic (FRP)	Board	1183	0.2252	1.6930		Fibre reinforced plastic is made by reinforcing fibres like carbon fibre, glass fibre etc. It is light weight, is resistant to corrosion and has good mechanical properties thus offering environmental benefits.

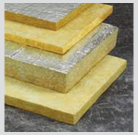
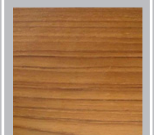
Name	Form	Density kg/m³	Thermal Conductivity W/(mK)	Specific Heat MJ/m³K	Image	Description
Fire Brick	Brick	2049	1.2729	1.2887		A firebrick is a rectangular block of clay which is modelled, baked and then treated to be heat resistant. Its properties can be adjusted by adding or adjusting the amount of refractory materials. It is widely used in construction industry for the purpose of making walls.
Floor Board	Board	954	0.2654	1.1423		Engineered wood flooring is made up of number of wood layers. It possesses great strength and stability which is achieved by running each layer of wood at a 90° angle to the layer above. It is widely used across the globe and can be installed over all types of subfloors.
Foam Cement Block	Block	581	0.1588	0.5359		Form cement block is a light weight block which is used in construction of non-structural walls in order to reduce the amount of structural concrete and steelwork. Its use leads to significant cost saving and also provides thermal insulation.
Ghana Teak Wood	Wood	529	0.2062	0.5769		Ghana teak wood has high strength, excellent durability and can withstand extreme weather conditions. It is also known for its aesthetic appearance. It is mostly used in flooring, furniture, wall cladding, window & door frames.
Glasswool	Insulation	49	0.0351	0.0339		Glass wool or fibre glass insulation is made up of fibre glasses which are arranged into a texture similar to wool. It is thermal and acoustical efficient and is available in form of sheets and rolls. It is inorganic in nature and is non-corrosive, non-combustible and doesn't absorb moisture.
Black Fine Granite	Stone	3535	2.4351	2.2511		Granite is a type of igneous rock consisting of mica, quartz and feldspar. It is granular and crystalline in texture. It has been used as flooring for decades now. It can be pink to grey in colour.
Black Coarse Granite	Stone	3473	2.5433	2.1996		Granite is a type of igneous rock consisting of mica, quartz and feldspar. It is granular and crystalline in texture. It has been used as flooring for decades now. Black Coarse granite as the name defines is coarse in nature.
Green Marble	Stone	2650	2.3720	2.5275		Marble is a metamorphic rock composed of recrystallized carbonate minerals mostly calcite. It has been in use for more than 450 years now.

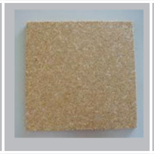
Name	Form	Density kg/m³	Thermal Conductivity W/(mK)	Specific Heat MJ/m³K	Image	Description
Green Rockwool	Insulation	96	0.0450	0.1089		Green Rockwool refers to a type of insulation commonly used in building construction, industrial plants, and in automotive applications.
Gypsum Board	Board	623	0.2527	0.6033		Gypsum board is also known as wallboard or drywall. It is made of plaster of paris and componenet of cement. It is used as sheathing for interior walls and ceiling and provides a smooth surface finish. The board is available in different thickness like 6mm, 12mm and 18mm.
Gypsum Powder	Powder	588	0.2020	1.1918		Gypsum powder is formed form gypsum stone by heating the stone. The powder is known for adding strength and viscosity to the material. It is used for plaster, paint and drywall.
Gypsum Powder from Board	Powder	542	0.1033	0.6260		Gypsum powder from board is formed form gypsum board. The powder is known for adding strength and viscosity to the material. It is used for plaster, paint and drywall.
Italian Black Granite	Stone	2911	2.3636	2.2349		Granite is a type of igneous rock consisting of mica, quartz and feldspar. It is granular and crystalline in texture. It has been used as flooring for decades now. It is used in bathrooms, kitchens etc.
Italian Marble	Stone	2630	2.7752	2.1869		Marble is a metamorphic rock composed of recrystallized carbonate minerals mostly calcite. It has been in use for more than 450 years now. It is mainly used as flooring and wall cladding in construction industry.
Jaisalmer Yellow Stone	Stone	3006	2.7447	2.0954		Jaisalmer Yellow is a type of limestone and is very fine grained as compared to other limestone. It has been used in monumental buildings and is used as flooring and cladding nowadays.
Jalore	Stone	2982	3.4412	1.9617		Granite is a type if igneous rock consisting of mica, quartz and feldspar. It is granular and crystalline in texture. It has been used as flooring for decades now. It is used in bathrooms, kitchens etc.

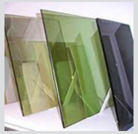
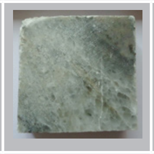
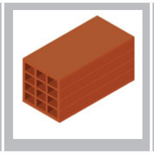
Name	Form	Density kg/m³	Thermal Conductivity W/(mK)	Specific Heat MJ/m³K	Image	Description
Kota Stone	Stone	3102	3.0229	2.0732		Kota Stone is a fine-grained variety of limestone which is quarried at Kota district, Rajasthan, India. It is available in greenish-blue and brown colour. Its strength and durability makes it an excellent stone and has been widely used for exterior as well as interior purpose.
Laminated Particle Board	Board	656	0.1841	1.2621		Particle board is made up of saw dust and other wood waste. It is an inexpensive material used in place of wood panelling or boards. It is used only for interior projects and is not much durable. It can be machined as per the customer need.
Lime Powder	Powder	607	0.1286	0.7078		Lime powder in an inorganic compound also called slaked lime. It is either white or colourless crystal. It is extensively used in construction industry.
Mangalore Roof Tile	Tile - Roof	2531	0.6051	1.2809		Mangalore tiles are red coloured tiles prepared from laterite clay. It is eco-friendly, cheap, durable and is available in different size and shapes as per users need. Due to vast availability of sizes and shapes they are easy to handle and install but precaution is needed as these are delicate and are vulnerable to breakage. These tiles can be used in many creative ways but their maintenance is an issue.
Ambaji Marble	Stone	3128	2.8108	2.1943		Marble is a metamorphic rock composed of recrystallized carbonate minerals mostly calcite. It has been in use for more than 450 years now. It is mainly used as flooring and wall cladding in construction industry.
Medium Density Fiberboard (MDF)	Board	133	0.2045	0.9610		Medium density fibreboard is a type of hardwood made from wood fibres forming panels by applying high pressure and temperature. It is stronger and denser than plywood, is flat and has no knots. Workability includes easy cutting, drilling, machining and filing without damaging the surface. It can also be painted to produce smooth surface. It is used for making wall panels, display cabinets and storage units.
Melamine Fiberboard	Board	807	0.2459	0.6509		Melamine Fibre board is used in the auto industry to create free-form shapes such as dashboards, rear parcel shelves, and inner door shells.
Mild Steel (MS)	Metal	7823	44.1170	4.1896		Mild Steel is one of the least expensive steel and most common metal used and is founded in almost every product created from metal. It is relatively hard, very durable and can be easily welded and annealed. It has poor resistance to corrosion and has to be protected. Its structural strength doesn't allow MS to be used for beams and girders.

Name	Form	Density kg/m³	Thermal Conductivity W/(mK)	Specific Heat MJ/m³K	Image	Description
Mineral Fiber - Celling	Board	364	0.0710	0.3222		Mineral fibre ceiling board is fire proof, mould proof, ensures better sound absorption and is a thermal insulator. It is eco-friendly and is used in indoor ceiling.
Mineral Fiber - Plain	Board	773	0.2739	0.6427		Mineral fibre plain board is fire proof, mould proof, ensures better sound absorption and is a thermal insulator. It is eco-friendly and is ideally suited for places where high privacy levels are required.
Oak Laminated Floor Tiles	Tile	949	0.2652	1.3389		Oak laminated floor tile is extremely durable, is resistant to damage and easier to keep clean. It is very easy to install and is much more affordable than wood flooring.
Concrete Paver Tiles	Tile	2210	1.7248	1.3413		Concrete paver tile is precast concrete form used widely as a tile. TIt is known for its strength, durability and east application. Workability includes laying of interlocking tiles without using grout, instead sand particles are spread over the pavers and tamped down thus they can be easily removed and reinstalled in case some service needs to be provided. They are available in various textures and colours and are mostly used in exterior pavement applications.
Paver Tile	Tile	2612	1.4763	1.2737		Paver tile looks like brick but just half as thick as brick. It is durable and frost-proof and come in all the colours that a brick comes into. They are used for flooring.
Plain & Prelaminated Particle Board	Board	902	0.2710	0.9740		Plain & pre laminated particle board is manufactured using plantation species of timber known for superior finish, high durability, excellent machinability and resistance to termite, water and moisture. It is eco-friendly wood based panel board which is cost effective and extremely versatile. It is used for making panel doors, flush doors, flooring, partitioning, false ceiling, wall panelling etc.
Plaster of Paris (POP) Powder	Powder	1000	0.1353	0.9526		Plaster of Paris is made by heating gypsum. It can be moulded in varies shapes and sizes after adding water to the powder. Its setting time is very less and is used in art, architecture, fireproofing, and medical applications.
Plywood	Board	697	0.2210	0.7258		Plywood is flexible, workable and re-usable. It is also resistant to cracking, splitting, shrinkage and twisting and has good strength. It is widely used in building and furniture industry.

Name	Form	Density kg/m³	Thermal Conductivity W/(mK)	Specific Heat MJ/m³K	Image	Description
Polyisocyanurate (PIR)	Insulation	40	0.0364	0.0685		The PIR “thermal blanket” insulates the framing materials thus reducing moisture possibility and improving overall R value of the building envelope. It is not ignitable and is suitable for building roof, wall insulation and for equipment insulation.
Polymer (Anisotropic)	Plastic	1743	0.5027	1.6968		A polymer is created through the process called polymerisation. It is used as wall panels, sealing, coating, roofing material and for piping system.
Polyurethane Foam (PUF)	Insulation	40	0.0372	0.0704		Flexible polyurethane foam is used for thermal insulation and is most often used in bedding and upholstery. Flexible polyurethane can be cut into various shapes. In construction rigid polyurethane is commonly used.
POP Board	Board	1080	0.4994	1.2167		POP is made by heating gypsum powder. POP board is a layer of plaster sandwiched between two sheets of card board. Plaster board puts very little pressure on the environment. The product is non-toxic and unwanted by-products from the process are minimal.
Porcelain Tile	Tile	2827	1.5331	1.6259		Porcelain tile is ceramic tile. It has very less water absorption rate and can be glazed or kept unglazed. It is used for flooring as well as wall cladding.
Pumice Square - Bronze Tile	Tile	2327	0.9907	0.4382		Bronze tiles is made of ceramic and various metal mixtures. It is engineered in a way that it look like bronze surface. It can be painted but surface needs to be conditioned before applying paint.
Quartz	Stone	2359	3.7603	1.8277		Natural Quartz is the hardest non- precious crystal stone mined directly from the earth. Quartz surfaces are created from pure natural Quartz. Its good looks and everlasting finish can be easily maintained by simple and routine care and can be used in areas prone to footfalls and weathering. It is mostly used as flooring material for commercial and residential projects.
Rajnagar Marble	Stone	3332	5.6405	2.7770		Marble is a metamorphic rock composed of recrystallized carbonate minerals mostly calcite. It has been in use for more than 450 years now. It is mainly used as flooring and wall cladding in construction industry.

Name	Form	Density kg/m^3	Thermal Conductivity W/(mK)	Specific Heat MJ/m^3K	Image	Description
Rigid Polyurethane (40 Kg/m3)	Insulation	40	0.0269	0.0766		Rigid polyurethane foam is a very versatile material having great combination of physical strength and mechanical properties. It can be used at places where insulation needs to be combined with load bearing. It is impact resistant, known for its longevity, space saving and has low maintenance.
Rigid Polyurethane (25 Kg/m3)	Insulation	25	0.0384	0.0763		Rigid polyurethane foam is a very versatile material having great combination of physical strength and mechanical properties. It can be used at places where insulation needs to be combined with load bearing. It is impact resistant, known for its longevity, space saving and has low maintenance.
Rockwool	Insulation	64	0.0461	0.0904		Rockwool insulation is made of actual rocks and minerals. It is also called stone wool insulation or mineral wool insulation. It is known for its thermal resistance and sound absorptivity. It is commonly used in building construction, industrial plants, and in automotive applications.
Rubber - Foam	Insulation	89	0.0561	0.1486		Foam rubber is manufactured by forming gas bubbles in a plastic mixture with the help of blowing agent. Foam rubber contains roughly 85 percent air and 15 percent rubber. Workability allows easy cutting and fixing. It is used as insulation, expansion joint filler in masonry and concrete work and filler support sealant in traffic bearing joints.
Rubber Wood	Wood	472	0.1679	0.5034		Rubberwood has a dense grain character with little tendency to wrap or crack. It is eco friendly as it is only harvested when it can no longer be used for its latex producing sap. Rubberwood has very less shrinkage and is one of the more stable construction materials. It is extensively used in furniture industry and for making kitchen accessories. Outdoor usage of the products is not recommended. Rubberwood latex is also used for rubber based products.
Saag Wood	Wood	959	0.2886	1.0258		Saag (Teak) is a yellowish brown timber having high oil content, high tensile strength and tight grain making it a suitable option for outdoor furniture applications. Easy workability but presence of silica in the wood causes severe blunting on edged tools. It is resistant to termite attacks and over time matures to silvery grey finish. Used for manufacturing of articles where weather resistance is required and also for indoor furnishing such as flooring, countertops, furniture, doors and window frames.
Sand	Powder	1600	0.3075	1.1343		Sand is composed of rock and mineral particles and is a granular material. Its composition highly depends on type of rock and mineral availability. In is widely used in building construction and landscaping.
Sandstone	Stone	2530	3.0097	1.5957		Sandstone is a sedimentary rock available in various colours. It is a valuable aquifer as it allows percolation of water and stores large quantities. It is also helpful to filter out pollutants from the surface and is a commonly used building material.

Name	Form	Density kg/m³	Thermal Conductivity W/(mK)	Specific Heat MJ/m³K	Image	Description
Serpentine Green Granite	Stone	3068	2.1363	2.4484		Serpentine Green Granite and can be identified by its marks, which look like the skin of a serpent. It is a type of igneous rock consisting of mica, quartz and feldspar. It is granular and crystalline in texture. It has been used as flooring for decades now. It is used in bathrooms, kitchens etc.
Soft Board	Board	274	0.0943	0.2753		Soft Board is a light coloured sheet made up of bagasse. It is soft and resilient and is known for its sound absorbing properties. It is available in variable thickness. It is used in wall and ceiling lining as acoustic boards.
Soft Board-High Density	Board	353	0.0983	0.2621		Soft Board is a light coloured sheet made up of bagasse. It is soft and resilient and is known for its sound absorbing properties. It is available in variable thickness. It is used in wall and ceiling lining as acoustic boards.
Stainless Steel (SS)	Metal	7950	13.5633	3.6351		Stainless steel is an ideal material as it requires low maintenance, is resistant to corrosion. It differs from the carbon steel by the mount of chromium present. The carbon steel rusts easily when exposed to moisture whereas stainless steel doesn't corrode, rust or stain but it is not fully stain proof. It is used in buildings for practical as well as aesthetic reasons.
Steam Beech Wood	Wood	241	0.2331	0.5512		Beech is pale coloured, medium to heavy weight, hard and tough wood having good strength and high abrasion resistance. Workability is easy despite of its hardness. It can be cut, drilled, planed and milled. Surface finishing of Beech is very straight forward as it can be stained, painted and polished. Beech can shrink considerable and is subject to movement as compared to other woods. It is used for furniture, interior furnishing, household equipment and plywood.
Straw Board	Board	760	0.2237	0.7098		Strawboard is made of 100% straw and is strong, lightweight and impact resistant. It can be used as an alternative to plasterboard. Workability includes easy cutting, machining, shaping and fixing. Strawboard when incorporated into partitions can achieve half an hour fire and impact resistance. It is recyclable and biodegradable and useful for preparing high quality building interior.
Teak Wood	Wood	665	0.2369	0.8412		Teak is a yellowish brown timber having high oil content, high tensile strength and tight grain making it a suitable option for outdoor furniture applications. Easy workability but presence of silica in the wood causes severe blunting on edged tools. It is resistant to termite attacks and over time matures to silvery grey finish. Used for manufacturing of articles where weather resistance is required and also for indoor furnishing such as flooring, countertops, furniture, doors and window frames.
Tempered Glass	Glass	2500	1.0493	1.9227		Tempered or toughened glass is one of the safety glass used at places where strength, safety and thermal resistance are important considerations. It is stronger, harder and brittle than standard glass and shatters into oval pebbles when broken. It is used in buildings for frameless assemblies, structurally loaded applications and any other application that would become dangerous in the event of human impact.

Name	Form	Density kg/m³	Thermal Conductivity W/(mK)	Specific Heat MJ/m³K	Image	Description
Tinted Glass	Glass	2500	1.0428	1.8904		Tinted glass is produced after treating the surface of a normal glass with film or coating thus reducing the light transmission through it. It can be coated with different type of coatings which can block as well as reflect the light.
Udaipur Brown Marble	Stone	3197	2.9210	2.2184		Marble is a metamorphic rock composed of recrystallized carbonate minerals mostly calcite. It has been in use for more than 450 years now.
V-Board	Board	1191	0.2977	0.8245		V-Board is a particle board considered as an inexpensive alternative to solid wood boards. It is produced by combining saw dust and other waste wood, provides a good insulation and has low thermal conductivity. It can be easily cut into sheets with the help of customised saws. V-Board is highly effective in maintaining a balanced temperature in air-conditioned spaces thus saving energy.
Veneered Particle Board	Board	788	0.2363	0.7075		Natural wood veneer is denser and very smooth. It is generally applied to particle board to provide high degree of finish. It is regarded as premium decorative finish and is widely used in office furniture, wall lining, false ceiling etc.
Vitrified Tile	Tile	2719	1.4786	1.8049		Vitrified tile has a low porosity and water absorption which makes it very strong and stain resistant. It has better mechanical strength, is scratch and stain resistant and is not affected by acids, alkalis and chemicals in comparison to marble and granites. It is mainly used for flooring purpose.
Resource Efficient Bricks (REB)	Brick	1520	0.6314	0.9951		Resource Efficient Brick is a hollow brick with low water absorptivity, better finish, improved crushing strength. It helps in resource saving due to its design and manufacturing. It helps in cutting down cost of the construction.
Wood	Wood	802	0.2652	0.8715		Wood is a hard, fibrous tissue found around the world. It is an organic material, a natural composite of cellulose fibres (which are strong in tension) embedded in a matrix of lignin which resists compression. It has been used for thousands of years for as a construction material.
Wood Pattern Chitodio	Stone	3126	3.4258	2.2852		Chitodio stones are available in different design and colours and is mainly used as flooring of super market, shopping mall, warehouse flooring, etc.