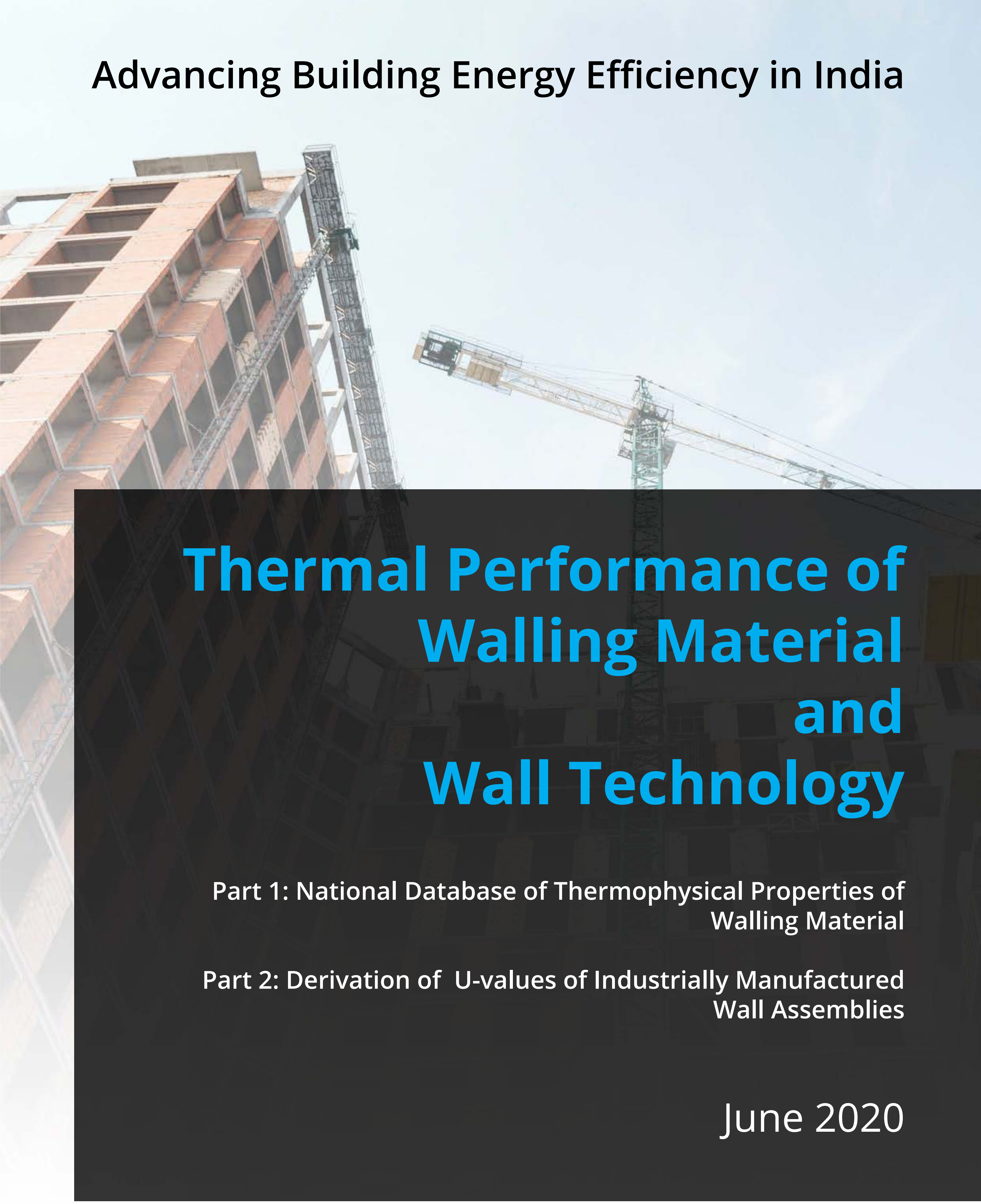
Advancing Building Energy Efficiency in India



Thermal Performance of Walling Material and Wall Technology

Part 1: National Database of Thermophysical Properties of Walling Material

Part 2: Derivation of U-values of Industrially Manufactured Wall Assemblies

June 2020

Greentech Knowledge Solutions Pvt. Ltd

SHAKTI SUSTAINABLE ENERGY FOUNDATION

CRDF CEPT RESEARCH AND DEVELOPMENT FOUNDATION

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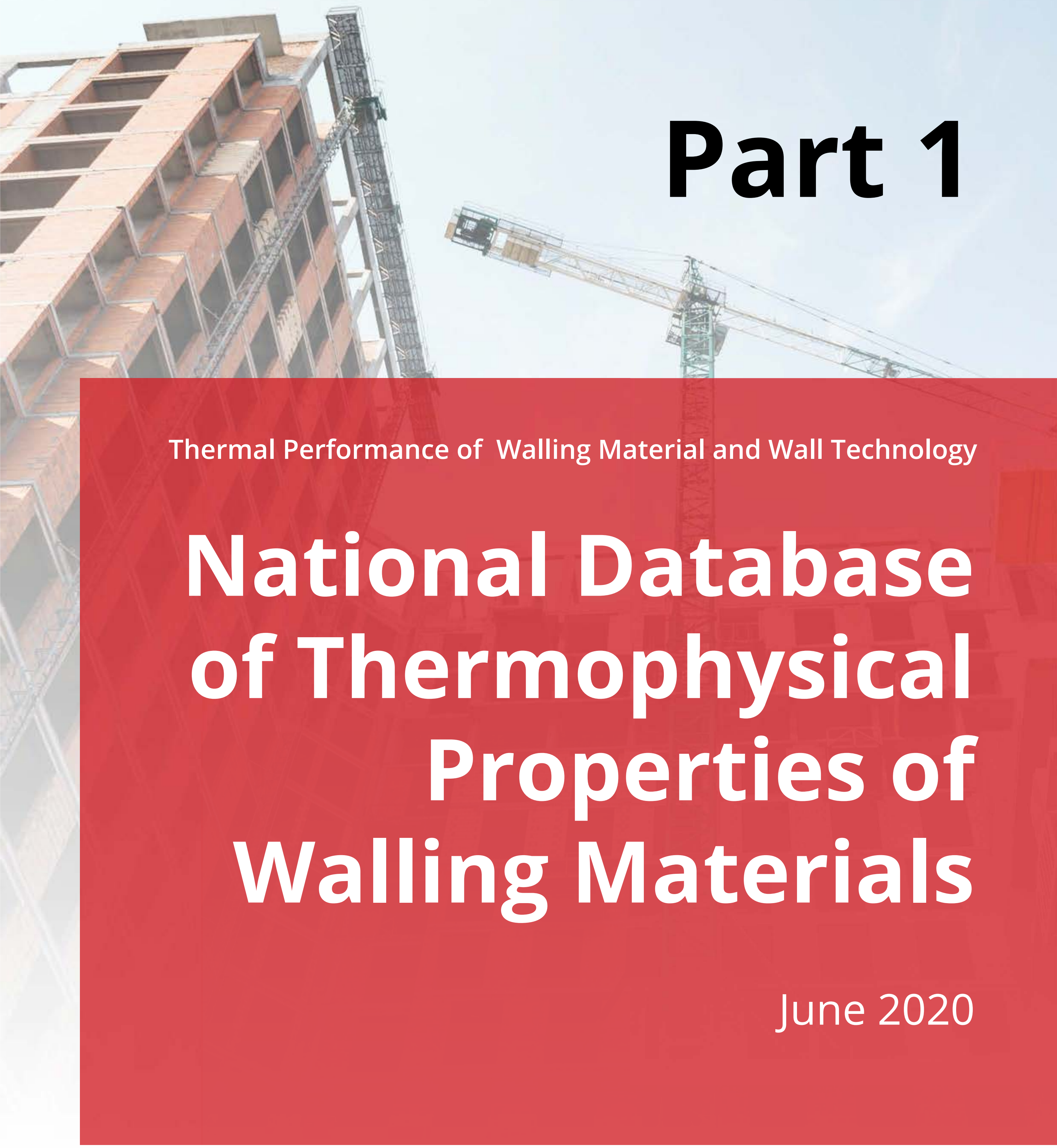

Part 1

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INTRODUCTION 1

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 thinktank 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 spacecooling. 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 (15W/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 firedclay brick, flyash 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 fortytwo samples of solid masonry building units from various Indian states/climatic zones. The properties measured for each sample are: bulk density, thermal conductivity, volumetric specific heat, water absorption, and compressive strength.
2. An approximate of the correlation between bulk 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 firedclay bricks, earlier studies pointed out that thermal conductivity of bricks is mainly dependent on their bulk density but, new studies (Gualtieri et al., 2010) and (Dondi et al., 2004) argued that other than bulk 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 bulk 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 bulk 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 steadystate, 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 steadystate conduction the overall thermal transmittance or (U-value) *($Wm^{-2}\ K^{-1}$)* of a wall composed of plane homogenous isotropic layers of materials is given as:

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

Where N is the number of layers in the construction, x_i (m) the thickness of layer i, λ_i *($Wm^{-1} K^{-1}$)* the thermal conductivity of layer i, R *(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 steadystate 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 1.1 gives representative values of thermal parameters for some common solids used in buildings (Davies, 2004).

Table 1.1: Representative thermal parameters of some common solids

	Thermal conductivity λ (W/m.K)	Bulk Density ρ (kg/m^3)	Specific heat C_p (J/kg.K)	Diffusivity $\alpha\times10^6$ (m^2/s)	Effusivity ϵ ($Ws^{0.5}/m^2.K$)
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. Chapter2 contains information on materials selected for measurements and their tested properties. Chapter3 gives materialwise test results and the various data plots that were measured. Chapter4 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.

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 firedclay bricks. In terms of the production of solid firedclay 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 firedclay 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 greenbricks; 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 firedclay bricks produced from mechanized plants are denser and have higher compressive strength as compared to the handmoulded bricks.

The use of flyash (a by-product of coal combustion) brick as an alternative to firedclay 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. Flyash bricks are made in mechanized plants where pan-mixer is used to mix flyash 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 lesscommon types of solid bricks or blocks used in construction include solid concrete, calcium silicate, autoclaved aerated concrete, compressed stabilized earth block, etc. Similar to flyash 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. Flyash 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)

A total of fortytwo samples were collected from thirteen different states of India in order to represent the wide range of solid masonry building units used in construction. Majority of the samples are of firedclay (twenty-three samples) and non-fired or cured bricks (nineteen samples). Individual datasheets containing information about the collection site and manufacturing processes are given in the annexure.

Table 2.1 shows the details of state-wise distribution of samples collected for measurements and Figure 2.1 shows their location on the map.

Table-2.1: State-wise distribution of collected samples

	Firedclay Brick	Flyash Brick	Concrete Brick	Concrete Block	Calcium Silicate Block	AAC	CLC	CSEB
Tamil Nadu	4	1	-	-	-	-	-	-
Telangana	1	-	-	-	-	-	-	-
Andhra Pradesh	1	-	-	1	-	-	-	-
Maharashtra	2	2	-	-	1	1	1	-
Gujarat	2	1	-	-	-	-	-	-
Bihar	1	1	-	-	-	-	-	-
Delhi & NCT	-	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	-	-	-	-	-
Total	23	10	1	2	1	2	1	1

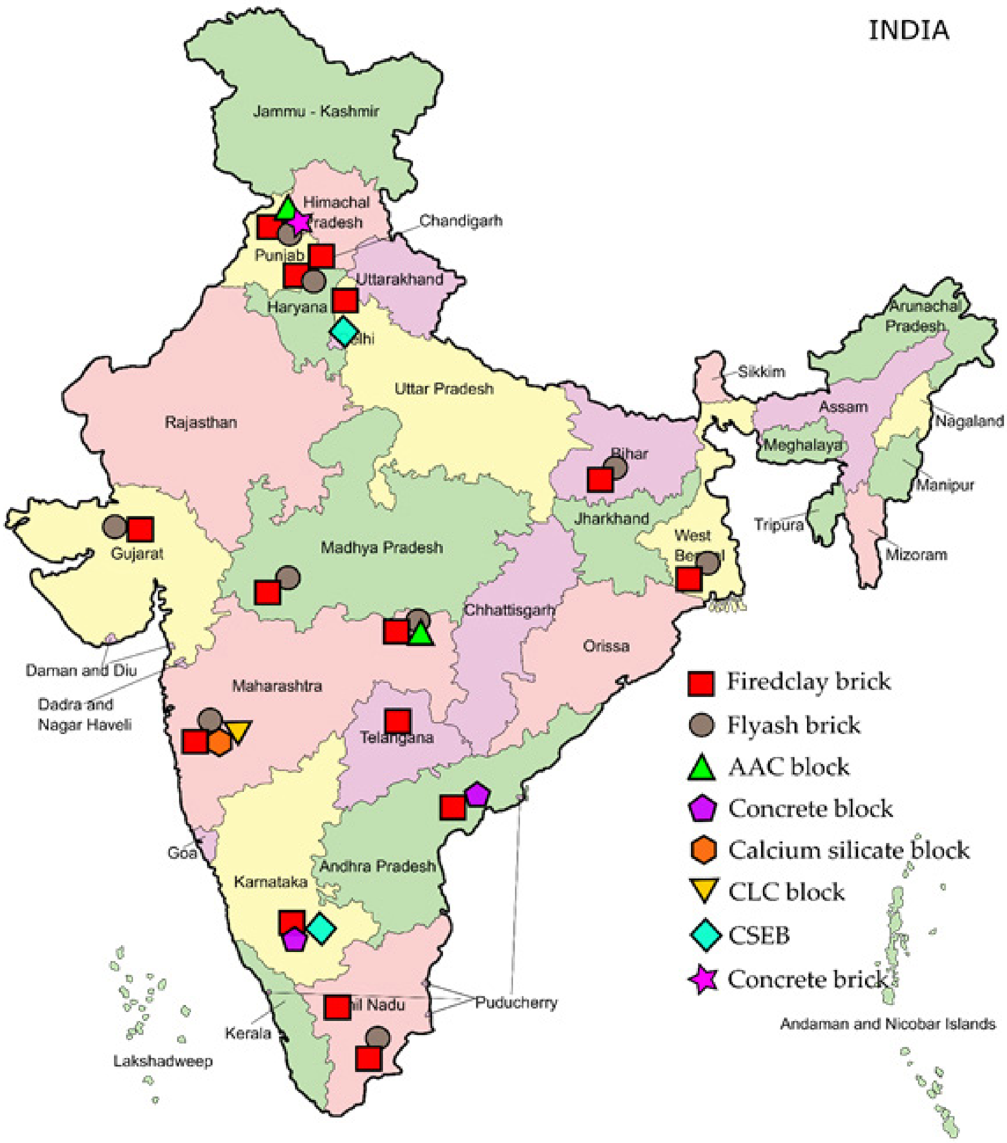


Figure-2.1: Location of collected samples

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 fortytwo 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 2.1 describes the instruments used and applicable testing standards followed by CARBSE for testing each parameter. Thermal conductivity and specific heat was measured using Thermal Constants analyser as per ISO/DIS 22007-2:2015 as seen in Table 2.2. Similarly, bulk density, water absorption, and compressive strength were measured following specific standards of measurement as seen in Table 2.2. The testing procedure specifying environmental conditions and sample requirements for each parameter is elaborated along with photographs of the samples in Annexure II.

Table 2.2: 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	Bulk 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)

The annexure contains individual datasheets with the measured thermophysical properties of all the fortytwo samples. Twenty-three samples of fired clay and nineteen samples of non-fired or cured bricks were collected. The number of samples collected are sufficient enough to statistically determine a correlation between any two parameters. Only these two types of masonry units are considered for examining the influence of bulk density on thermal conductivity.

3.1 Fired Clay Brick

Table 3.1 shows the manufacturing process and location and Table 3.2 shows average value of measured properties of the samples tested.

Bulk density and thermal conductivity of hand-moulded bricks range from 1264-1887 kg/m^3 and 0.38-0.76 $W/m.K$ respectively, whereas the bulk density and thermal conductivity for machine moulded (extruded or soft-mud moulded) bricks varies between 1648-2119 kg/m^3 and 0.41-1.12 $W/m.K$ respectively.

Figure 3.1 shows the variation of thermal conductivity with bulk density for firedclay bricks. Using MicrosoftExcel, an exponential correlation is fit to the data. Goodness of fit (R^2=0.74) shows that bulk density is a major factor that governs thermal conductivity of solid firedclay bricks. Thus, for a given value of bulk density ρ (kg/m^3), the following equation can be used to make an estimation of thermal conductivity λ ($W/m.K$) for firedclay bricks:

$$\lambda = 0.065e^{(0.0012\rho)} \quad (1250 < \rho < 2150) \ldots (3.1)$$

Table-3.1: Location and manufacturing process of firedclay samples

S/N	Sample	Manufacturing Process (Moulding)	Location
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, Telengana
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

Table-3.2: Average value of measured properties of firedclay samples

S. N.	Sample	Bulk Density ρ (kg/m³)	Thermal conductivity λ (W/m.K)	Specific heat C_p (J/kg.K)	Compressive strength (MPa)	Water absorption (%)
Hand-moulding						
1	RB01	1599	0.48	907.8	14.83	21
2	RB02	1777	0.60	921.6	16.54	15
3	RB04	1654	0.57	917.5	23.08	19
4	RB06	1887	0.76	927.0	20.23	12
5	RB07	1738	0.53	960.4	7.21	16
6	RB09	1604	0.39	909.0	6.1	23
7	RB10	1512	0.42	926.5	5.32	26
8	RB11	1447	0.50	936.6	10.01	24
9	RB14	1503	0.42	935.9	4.88	26
10	RB15	1264	0.38	927.8	4.16	32
11	RB20	1780	0.55	952.9	18.68	15
12	RB21	1716	0.54	923.1	17.8	17
13	RB23	1819	0.74	978.6	25.8	13
Extrusion						
1	RB03	2119	0.97	916.1	58.21	7
2	RB05	2028	1.12	955.2	54	10
3	RB12	1975	0.80	928.1	26.83	12
4	RB18	1895	0.58	924.3	19.82	14
5	RB19	1958	0.65	947.2	10.79	13
Soft mud moulding						
1	RB13	1807	0.59	934.8	13.48	17
2	RB16	1657	0.42	940.4	7.51	19
3	RB17	1648	0.41	927.5	5.71	20
4	RB22	1798	0.64	918.5	26.17	14
Water-struck moulding						
1	RB08	1737	0.51	946.8	7.76	16

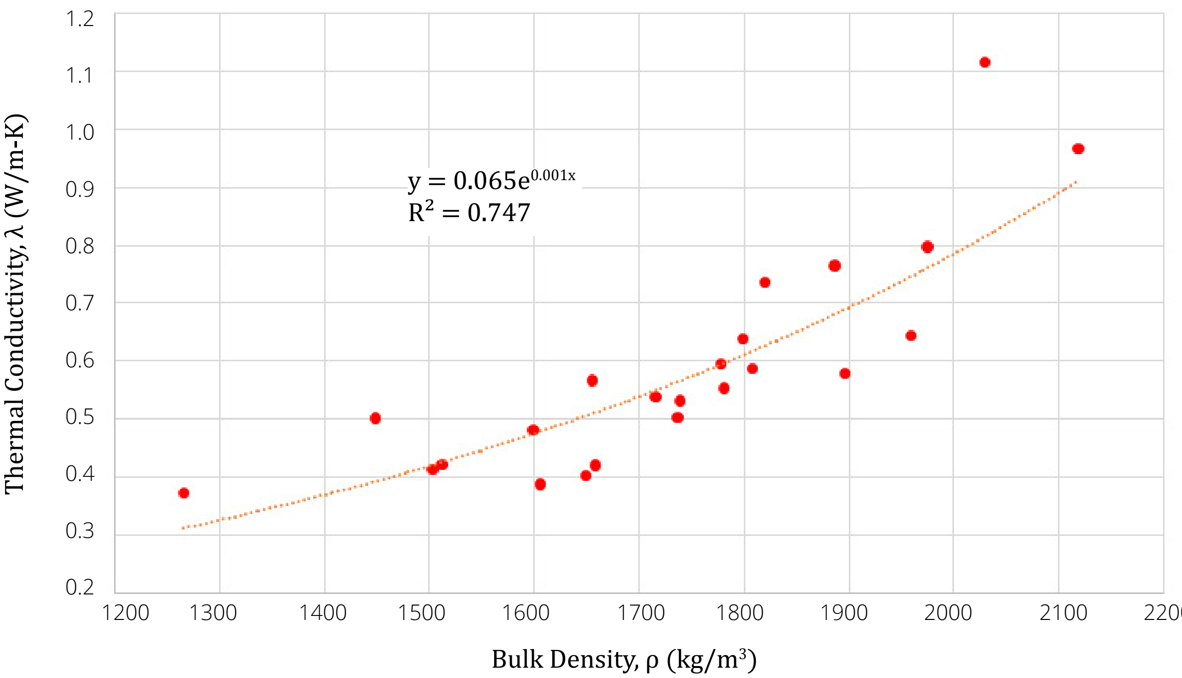


Figure-3.1: Thermal conductivity as a function of bulk density for firedclay bricks

3.2 Non-Fired (Cured) Brick

Table 3.3 shows the source location and Table 3.4 shows the average value of measured properties of the tested flyash brick samples. All the flyash brick samples that were collected were manufactured through machine-moulding process.

Table 3.5 shows the sample type and location and Table 3.6 shows average value of measured properties of other non-fired walling material samples tested.

Table-3.3: Source location of the flyash brick samples

S. N.	Sample	Location
1	FB01	Kolkata, West Bengal
2	FB02	Jhajjar, Haryana
3	FB03	Patna, Bihar
4	FB04	Najafgarh, NCT
5	FB05	Chandigarh, Punjab
6	FB06	Ahmedabad, Gujarat
7	FB07	Pune, Maharashtra
8	FB08	Indore, Madhya Pradesh
9	FB09	Nagpur, Maharashtra
10	FB10	Madurai, Tamil Nadu

Table-3.4: Average value of measured properties of flyash 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 (%)
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

Table-3.5: Source location of other non-fired walling material samples

S. N.	Sample	Sample type	Location
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

Table-3.6: Average value of measured properties of other walling material samples

S/N	Sample	Bulk Density ρ (kg/m³)	Thermal conductivity λ (W/m.K)	Specific heat C_p (J/kg.K)	Compressive strength (MPa)	Water absorption (%)
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

Figure 3.2 shows the variation of thermal conductivity with bulk density for non-fired bricks. Using MicrosoftExcel, an exponential correlation is fit to the data. Goodness of fit (R^2=0.87) indicates a strong correlation between bulk density and thermal conductivity.

For a given value of bulk density ρ (kg/m³), the following equation can be used to build an estimate of thermal conductivity λ (W/m.K) for non-fired bricks:

$$\lambda = 0.0902e^{(0.0011\rho)}\ (600 < \ \rho\ < 2100)\ ...\ (3.2)$$

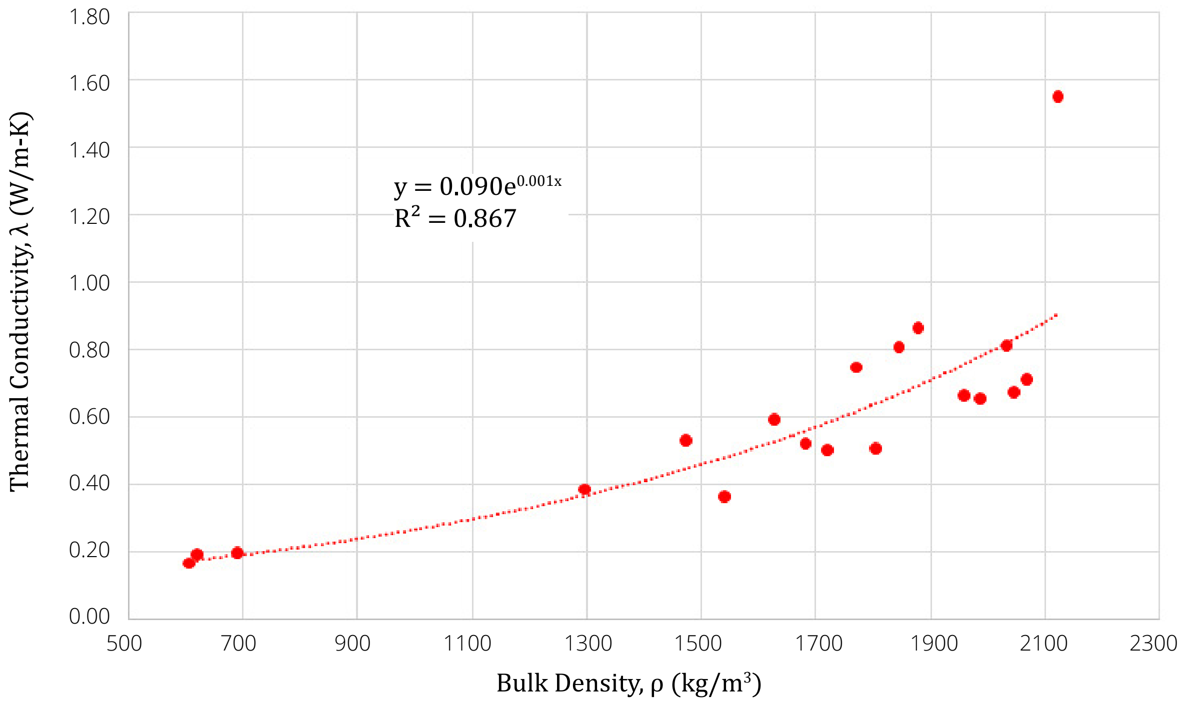


Figure-3.2: Thermal conductivity as a function of bulk density for non-fired bricks

CALCULATION OF RETV 4

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 steadystate 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.

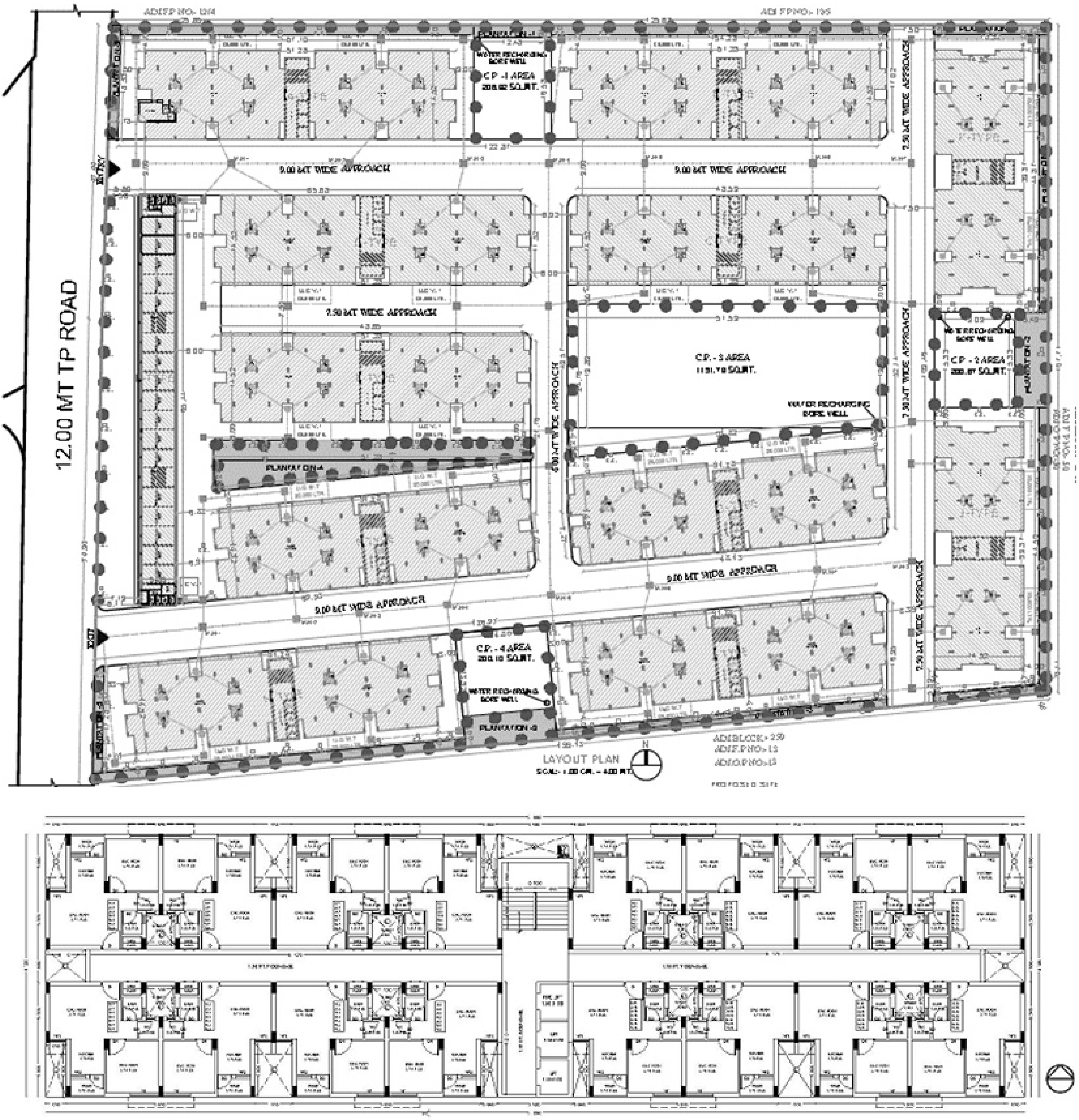


Figure-4.1: Site plan and typical unit plan of SMARTGHAR-III project, Rajkot

4.1 Sample Housing Project

A sevenstorey housing project (SMARTGHAR-III) in Rajkot (Gujarat) has been selected to calculate RETV. The carpet area of each dwelling unit is 26.6 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 4.1. 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.

Table 4.1 provides U-value of 200mm thick wall of each tested walling unit, with 15mm plaster on both the sides. Figure 4.2 shows the residential envelope transmittance values (RETV) for the given sample housing envelope taking different external wall materials.

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. Thirtyone, out of fortythree 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 firedclay (excluding extruded bricks) and flyash 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.

Table-4.1: U-values for different walling material samples

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
1	RB01	Firedclay brick	1.60
2	RB02	Firedclay brick	1.83
3	RB03	Firedclay brick	2.39
4	RB04	Firedclay brick	1.77
5	RB05	Firedclay brick	2.56
6	RB06	Firedclay brick	2.11
7	RB07	Firedclay brick	1.70
8	RB08	Firedclay brick	1.64
9	RB09	Firedclay brick	1.37
10	RB10	Firedclay brick	1.46
11	RB11	Firedclay brick	1.63
12	RB12	Firedclay brick	2.16
13	RB13	Firedclay brick	1.81
14	RB14	Firedclay brick	1.44
15	RB15	Firedclay brick	1.34
16	RB16	Firedclay brick	1.45
17	RB17	Firedclay brick	1.42
18	RB18	Firedclay brick	1.80
19	RB19	Firedclay brick	1.92
20	RB20	Firedclay brick	1.74
21	RB21	Firedclay brick	1.72
22	RB22	Firedclay brick	1.91
23	RB23	Firedclay brick	2.07
24	FB01	Flyash brick	2.25
25	FB02	Flyash brick	2.16
26	FB03	Flyash brick	1.69
27	FB04	Flyash brick	1.37
28	FB05	Flyash brick	1.64
29	FB06	Flyash brick	1.30
30	FB07	Flyash brick	1.96
31	FB08	Flyash brick	1.67
32	FB09	Flyash brick	1.92
33	FB10	Flyash brick	1.63
34	AB01	Autoclaved aerated concrete block	0.70
35	AB02	Autoclaved aerated concrete block	0.70
36	EB01	Compressed stabilized earth block	1.81
37	EB02	Compressed stabilized earth block	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	Cellular light weight concrete block	0.80

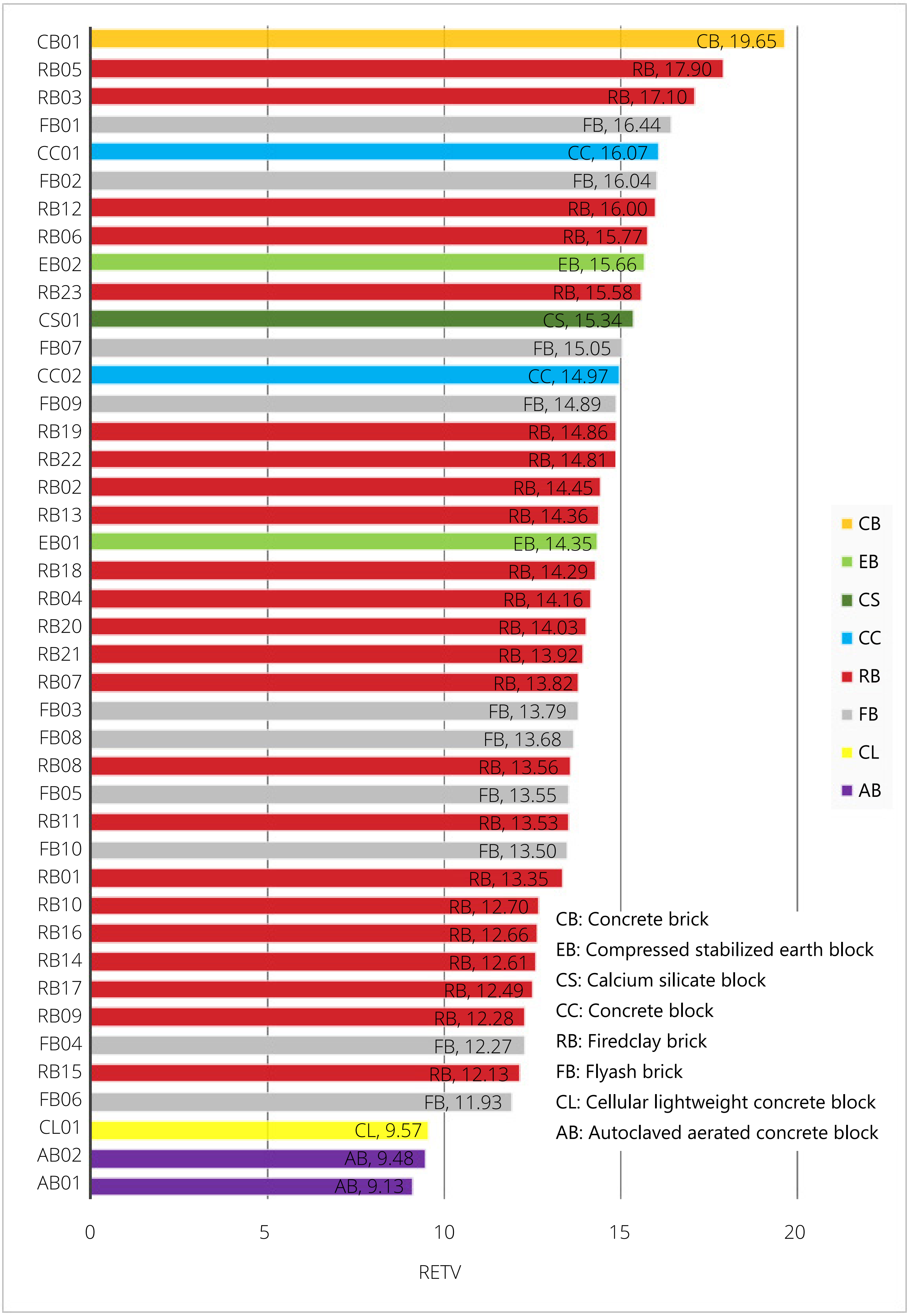


Figure-4.2: RETV values corresponding to various walling materials for a sample envelope

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. Measured in Kg/m^3 as per IS 3069:1994.

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 Section2.2. 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

A definite number of samples were required for testing each parameter based on the applicable standards mentioned in Section-2.2. TableA2.1 shows the number of samples needed for each test as per standards (cut or fullsized 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 as seen in FigureA2.3.

Sample tag

Each of the received fortytwo 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 FigureA2.1. TableA2.2 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 FigureA2.1. 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-A2.1: Number of samples required for each test as per standard

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
2	Fly ash Bricks (FB)	3	5		5
3	Solid concrete brick (CB)	3	5		5
4	Solid concrete blocks (CC)	3	3		12
5	Calcium silicate block (CS)	3	5		5
6	AAC blocks (AB)	3	3		12
7	Cellular light weight concrete block (CL)	3	3		12
8	CSEB (EB)	3	5		5

Figure-A2.1:Illustration to explain sample tag (top) and photograph of tagged bricks belonging to set 01 (left) & set 05 (right)

Table-A2.2: Different types material samples received for testing and the corresponding abbreviations assigned to them.

S. N	Abbreviation	Material type
1	RB	Fired clay brick
2	FB	Flyash 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)

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 FigureA2.2. Additionally, the Inert Gas Oven was used for pre conditioning the samples as described below.

Figure-A2.2: Photograph of thermal constant analyser testing brick samples using transient plane source method

Preconditioning

1. Three masonry unit samples as shown in FigureA2.3 was dried in the inert gas oven at a temperature of 105 °C for the period of 24 hrs. as seen in FigureA2.4.
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 FigureA2.2. 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 FigureA2.5 and the average was reported.

3 Full sized brick sample (in case of bricks) / 3 block samples cut from full sized blocks (in case of blocks)

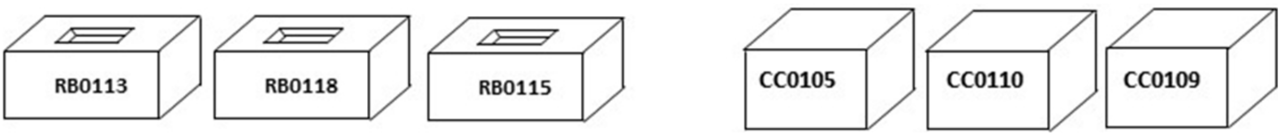


Figure-A2.3: Illustration showing number of masonry units needed for testing thermal conductivity and specific heat

Figure-A2.4: Photograph of the Inert Gas Oven (left) & bricks prepared for drying (right)

Figure-A2.5: Photographs demonstrating different combinations of brick specimens placed for measurement and hot disk probe sandwiched between two samples of fireclay 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:

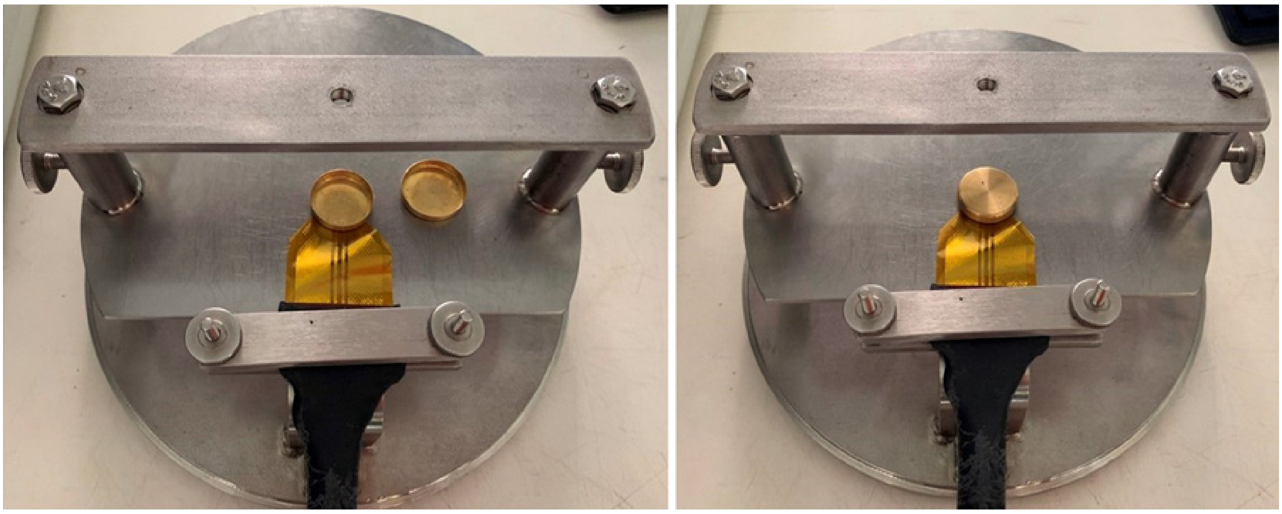


Figure-A2.6: Reference Measurement

Procedure

1. Initially a reference measurement was carried out by keeping the gold disk sensor empty as seen in FigureA2.6.

2. A small homogeneous piece of brick (test sample) without any air cavity was cut from the conditioned brick as seen in FigureA2.7.

3. As seen in FigureA2.8, 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.

4. The test sample was dried and the weight of the dried test sample was measured as seen in FigureA2.9.

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 FigureA2.10, and providing values of the reference measurement, the exterior volume and the weight of the test sample of the brick.

Figure-A2.7: Test Sample Preparation

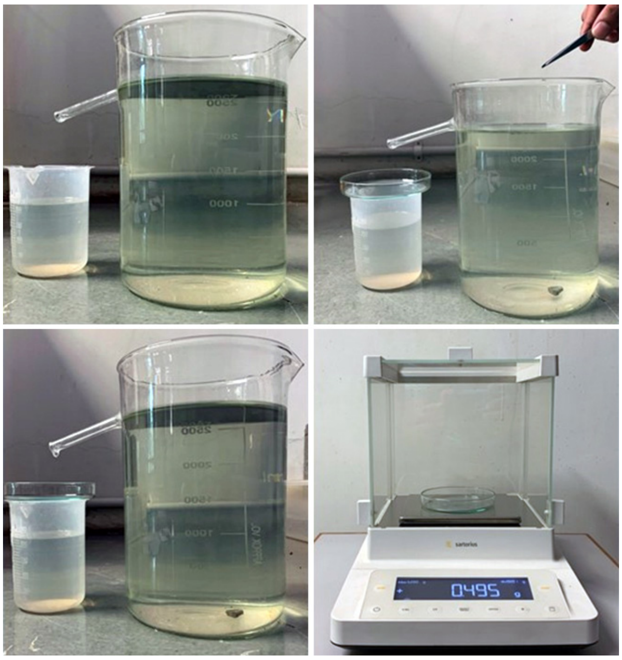


Figure-A2.8: Exterior Volume Measurement

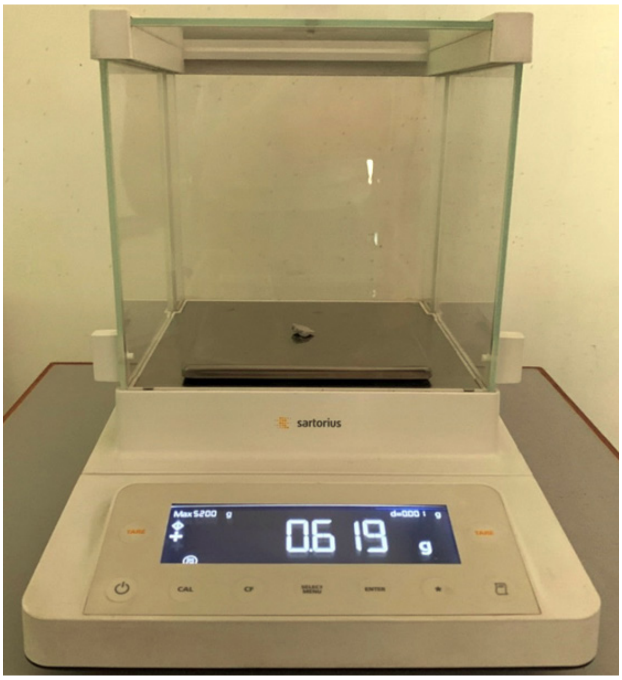


Figure-A2.9: Weight measurement of the dried test sample

Figure-A2.10: Specific heat capacity measurement

Bulk Density

Bulk density was measured based on ASTM C20. The instruments used were inert gas oven, water bath and precision weighing. Since measurement for Bulk 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

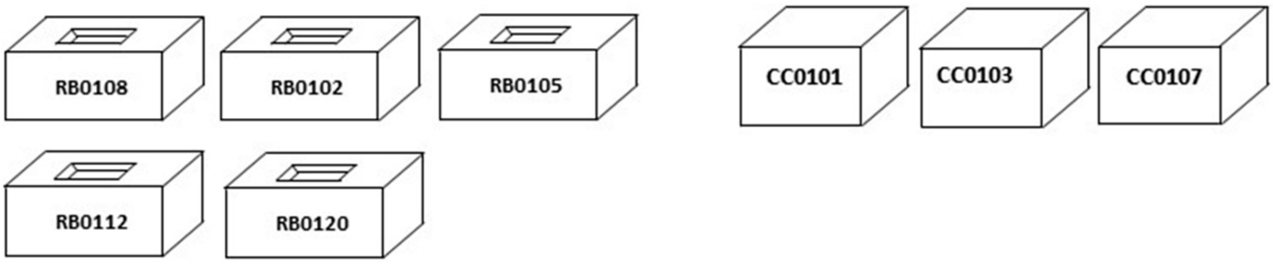
1. Five bricks or three block sample as seen in FigureA2.11, were dried at a temperature of 105°C until a constant mass was achieved.
2. After drying, the sample was cooled to room temperature and its weight was obtained denoted by dry mass (D) as seen in FigureA2.12.
3. After dry mass measurement, the sample was submerged into boiling water for the period of 2 hours as seen in FigureA2.13.
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 FigureA2.13 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 FigureA2.14.
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 FigureA2.14.

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



5 Full sized block samples (in case of bricks) / 3 block samples cut from full sized blocks (in case of blocks)

Figure-A2.11: Illustration showing number of masonry units allotted for testing dry density and water absorption

(a) *(b)*

(a) Figure-A2.12: Photograph showing dried sample being weighed to get dry mass (D)

(b) Figure-A2.13: Photograph showing dried brick samples being boiled (left) and brick samples immersed in water afterwards (right) as per the procedure.

Figure-A2.14: 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 FigureA2.4 and FigureA2.12, A2.13 (right) and A2.14 (right).

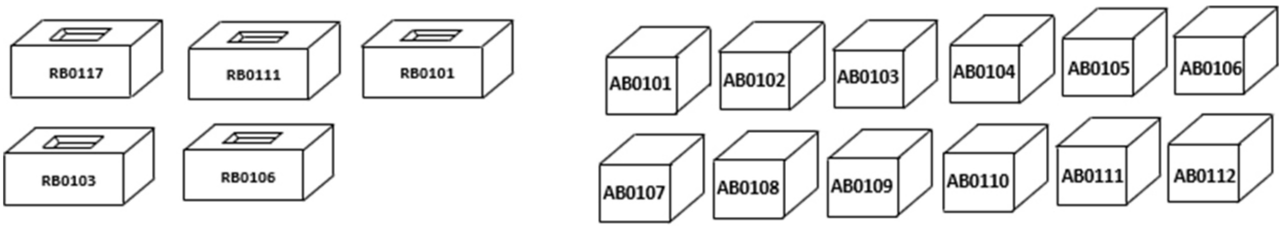
Measurement

1. Five brick or three block samples as seen in FigureA2.11 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 FigureA2.12.
3. After dry weight measurement, the sample was submerged into clean water kept at a temperature of 27 ± 2°C for 24 hrs. as seen in FigureA2.13 (right).
4. After 24 hrs., 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).

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



5 Full sized brick samples (in case of bricks) /12 block samples cut from full sized blocks (in case of blocks)

Figure-A2.15: Illustration showing the number of brick and block samples required for the compressive strength test.

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 FigureA2.15 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.
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 FigureA2.16.
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.

Figure-A2.16: Photograph of mortar filled bricks ready to be tested.

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 FigureA2.17, and load was applied axially at a uniform rate of 14 N/mm^2 per minute till failure occurred.
2. Maximum load at failure was noted.

Calculation

Compressive strength was calculated as:

Compressive strength in

$$N/mm^2 = \frac{\textit{Maximum load at failure in N (kgf)}}{\textit{Average area of the bed faces in mm2}(cm^2)}$$

Figure-A2.17: Photograph of Compression testing machine

Annexure-III: Measurement Datasheets

Datasheet 01

General information	
Sample type	Handmoulded 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 pugmill) • **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	
Bulk density, ρ (kg/m^3)	1599
Thermal conductivity, λ (W/m-K)	0.4847
Specific heat, C (J/kg-K)	907.8
Water absorption, (%)	21
Compressive strength, σ (N/mm2)	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	
Bulk density, ρ (kg/m³)	1878
Thermal conductivity, λ (W/m-K)	0.8619
Specific heat, C (J/kg-K)	938.2
Water absorption, (%)	12
Compressive strength, σ (N/mm2)	19.98

Datasheet 03

General information	
Sample type	Handmoulded 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 pugmill) • **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	
Bulk density, ρ (kg/m³)	1777
Thermal conductivity, λ (W/m-K)	0.5988
Specific heat, C (J/kg-K)	921.6
Water absorption, (%)	15
Compressive strength, σ (N/mm2)	16.54

Datasheet 04

General information	
Sample type	Extruded 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 pugmill) • **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	
Bulk density, ρ (kg/m^3)	2119
Thermal conductivity, λ (W/m-K)	0.9694
Specific heat, C (J/kg-K)	916.1
Water absorption, (%)	7
Compressive strength, σ (N/mm2)	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	
Bulk density, ρ (kg/m³)	1844
Thermal conductivity, λ (W/m-K)	0.802
Specific heat, C (J/kg-K)	924.8
Water absorption, (%)	16
Compressive strength, σ (N/mm2)	12.43

Datasheet 06

General information	
Sample type	Handmoulded 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 pugmill) • **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

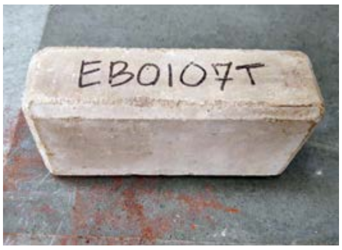
Thermal and physical properties	
Bulk density, ρ (kg/m^3)	1654
Thermal conductivity, λ (W/m-K)	0.5668
Specific heat, C (J/kg-K)	917.5
Water absorption, (%)	19
Compressive strength, σ (N/mm2)	23.08

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	
Bulk density, ρ (kg/m³)	1475
Thermal conductivity, λ (W/m-K)	0.5278
Specific heat, C (J/kg-K)	962.0
Water absorption, (%)	23
Compressive strength, σ (N/mm2)	9.02

Datasheet 08

General information	
Sample type	Compressed stabilized earth blocks 
Sample number	EB01
Date of collection	February 15, 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	
Bulk density, ρ (kg/m³)	1630
Thermal conductivity, λ (W/m-K)	0.5883
Specific heat, C (J/kg-K)	908.3
Water absorption, (%)	22
Compressive strength, σ (N/mm2)	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 and 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	
Bulk density, ρ (kg/m³)	1299
Thermal conductivity, λ (W/m-K)	0.387
Specific heat, C (J/kg-K)	924.0
Water absorption, (%)	27
Compressive strength, σ (N/mm2)	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 pugmill) • **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 petcoke 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	
Bulk density, ρ (kg/m³)	2028
Thermal conductivity, λ (W/m-K)	1.119
Specific heat, C (J/kg-K)	955.2
Water absorption, (%)	10
Compressive strength, σ (N/mm2)	54

Datasheet 11

General information	
Sample type	Handmoulded 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 pugmill) • **Shaping:** Hand moulding. • **Drying:** Natural drying • **Firing:** Bricks are fired in an induced draught Zigzag kiln. • **Fuel:** Petcoke
Fuel consumption	12 ton petcoke per lakh bricks
Production capacity	50,000 bricks per day
Address/Contact	Bharat bricks Mr. Kulbhushan, +91-9425052825

Thermal and physical properties	
Bulk density, ρ (kg/m^3)	1887
Thermal conductivity, λ (W/m-K)	0.7645
Specific heat, C (J/kg-K)	927.0
Water absorption, (%)	12
Compressive strength, σ (N/mm2)	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 and cement
Address/Contact	Mr. Jaamavar (contractor), +91-9915068553

Thermal and physical properties	
Bulk density, ρ (kg/m^3)	1807
Thermal conductivity, λ (W/m-K)	0.5042
Specific heat, C (J/kg-K)	961.1
Water absorption, (%)	15
Compressive strength, σ (N/mm2)	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	
Bulk density, ρ (kg/m³)	2122
Thermal conductivity, λ (W/m-K)	1.546
Specific heat, C (J/kg-K)	920.0
Water absorption, (%)	7
Compressive strength, σ (N/mm2)	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
Address/Contact	Nisarg Prajapati (+91- 9898864332)

Thermal and physical properties	
Bulk density, ρ (kg/m³)	1543
Thermal conductivity, λ (W/m-K)	0.3594
Specific heat, C (J/kg-K)	908.0
Water absorption, (%)	27
Compressive strength, σ (N/mm2)	5.05

Datasheet 15

General information	
Sample type	Handmoulded 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	
Bulk density, ρ (kg/m³)	1738
Thermal conductivity, λ (W/m-K)	0.5313
Specific heat, C (J/kg-K)	960.4
Water absorption, (%)	16
Compressive strength, σ (N/mm2)	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: S**lurry preparation involves clay crushing (hammer mill + roller mill) + double shaft mixer • **Shaping:** Machine (press) 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	
Bulk density, ρ (kg/m³)	1737
Thermal conductivity, λ (W/m-K)	0.5051
Specific heat, C (J/kg-K)	946.8
Water absorption, (%)	16
Compressive strength, σ (N/mm2)	7.76

Datasheet 17

General information	
Sample type	Handmoulded 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	
Bulk density, ρ (kg/m³)	1604
Thermal conductivity, λ (W/m-K)	0.3876
Specific heat, C (J/kg-K)	909.0
Water absorption, (%)	23
Compressive strength, σ (N/mm2)	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	
Bulk density, ρ (kg/m³)	2071
Thermal conductivity, λ (W/m-K)	0.7069
Specific heat, C (J/kg-K)	969.2
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	
Bulk density, ρ (kg/m³)	693
Thermal conductivity, λ (W/m-K)	0.1932
Specific heat, C (J/kg-K)	932.2
Water absorption, (%)	78
Compressive strength, σ (N/mm2)	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	
Bulk density, ρ (kg/m³)	2048
Thermal conductivity, λ (W/m-K)	0.67
Specific heat, C (J/kg-K)	976.2
Water absorption, (%)	12
Compressive strength, σ (N/mm2)	15.16

Datasheet 21

General information	
Sample type	Handmoulded 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	
Bulk density, ρ (kg/m^3)	1512
Thermal conductivity, λ (W/m-K)	0.4244
Specific heat, C (J/kg-K)	926.5
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% flyash, 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	
Bulk density, ρ (kg/m^3)	1682
Thermal conductivity, λ (W/m-K)	0.5172
Specific heat, C (J/kg-K)	936.0
Water absorption, (%)	19
Compressive strength, σ (N/mm2)	10.14

Datasheet 23

General information	
Sample type	Handmoulded 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	
Bulk density, ρ (kg/m^3)	1447
Thermal conductivity, λ (W/m-K)	0.5016
Specific heat, C (J/kg-K)	936.6
Water absorption, (%)	24
Compressive strength, σ (N/mm2)	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 flyash, 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	
Bulk density, ρ (kg/m³)	1989
Thermal conductivity, λ (W/m-K)	0.6502
Specific heat, C (J/kg-K)	930.0
Water absorption, (%)	13
Compressive strength, σ (N/mm2)	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	
Bulk density, ρ (kg/m³)	608
Thermal conductivity, λ (W/m-K)	0.1669
Specific heat, C (J/kg-K)	875.5
Water absorption, (%)	72
Compressive strength, σ (N/mm2)	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	
Bulk density, ρ (kg/m³)	1975
Thermal conductivity, λ (W/m-K)	0.7969
Specific heat, C (J/kg-K)	928.1
Water absorption, (%)	12
Compressive strength, σ (N/mm2)	26.83

Datasheet 27

General information	
Sample type	Solid burnt clay bricks (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	
Bulk density, ρ (kg/m³)	1807
Thermal conductivity, λ (W/m-K)	0.5893
Specific heat, C (J/kg-K)	934.8
Water absorption, (%)	17
Compressive strength, σ (N/mm2)	13.48

Datasheet 28

General information	
Sample type	Compressed stabilized earth blocks 
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	
Bulk density, ρ (kg/m³)	1773
Thermal conductivity, λ (W/m-K)	0.7493
Specific heat, C (J/kg-K)	934.8
Water absorption, (%)	16
Compressive strength, σ (N/mm2)	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	
Bulk density, ρ (kg/m³)	2032
Thermal conductivity, λ (W/m-K)	0.8071
Specific heat, C (J/kg-K)	912.8
Water absorption, (%)	9
Compressive strength, σ (N/mm2)	10.04

Datasheet 30

General information	
Sample type	Handmoulded Solid burnt clay bricks 
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	
Bulk density, ρ (kg/m^3)	1503
Thermal conductivity, λ (W/m-K)	0.4162
Specific heat, C (J/kg-K)	935.9
Water absorption, (%)	26
Compressive strength, σ (N/mm2)	4.88

Datasheet 31

General information	
Sample type	Concrete block 
Sample number	CC02
Date of collection	April 16, 2019
Location	Yam, 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	
Bulk density, ρ (kg/m^3)	1961
Thermal conductivity, λ (W/m-K)	0.6601
Specific heat, C (J/kg-K)	928.9
Water absorption, (%)	13
Compressive strength, σ (N/mm2)	6.8

Datasheet 32

General information	
Sample type	Handmoulded Solid burnt clay bricks 
Sample number	RB15
Date of collection	April 17, 2019
Location	Karimnagar, Telengana
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	
Bulk density, ρ (kg/m^3)	1264
Thermal conductivity, λ (W/m-K)	0.3757
Specific heat, C (J/kg-K)	927.8
Water absorption, (%)	32
Compressive strength, σ (N/mm2)	4.16

Datasheet 33

General information	
Sample type	Solid burnt clay bricks 
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: ▪ Soft mud moulding machine (locally made): 10,000 bricks per day ▪ 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	
Bulk density, ρ (kg/m³)	1657
Thermal conductivity, λ (W/m-K)	0.4206
Specific heat, C (J/kg-K)	940.4
Water absorption, (%)	19
Compressive strength, σ (N/mm2)	7.51

Datasheet 34

General information	
Sample type	Solid burnt clay bricks 
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	
Bulk density, ρ (kg/m^3)	1648
Thermal conductivity, λ (W/m-K)	0.4061
Specific heat, C (J/kg-K)	927.5
Water absorption, (%)	20
Compressive strength, σ (N/mm2)	5.71

Datasheet 35

General information	
Sample type	Solid burnt clay bricks 
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	
Bulk density, ρ (kg/m³)	1895
Thermal conductivity, λ (W/m-K)	0.5817
Specific heat, C (J/kg-K)	924.3
Water absorption, (%)	14
Compressive strength, σ (N/mm2)	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 Flyash + 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	
Bulk density, ρ (kg/m^3)	1722
Thermal conductivity, λ (W/m-K)	0.4989
Specific heat, C (J/kg-K)	925.6
Water absorption, (%)	20
Compressive strength, σ (N/mm2)	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	
Bulk density, ρ (kg/m³)	1958
Thermal conductivity, λ (W/m-K)	0.6469
Specific heat, C (J/kg-K)	947.2
Water absorption, (%)	13
Compressive strength, σ (N/mm2)	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	
Bulk density, ρ (kg/m³)	1780
Thermal conductivity, λ (W/m-K)	0.5532
Specific heat, C (J/kg-K)	952.9
Water absorption, (%)	15
Compressive strength, σ (N/mm2)	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	
Bulk density, ρ (kg/m³)	1716
Thermal conductivity, λ (W/m-K)	0.5415
Specific heat, C (J/kg-K)	923.1
Water absorption, (%)	17
Compressive strength, σ (N/mm2)	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/cm2) 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	
Bulk density, ρ (kg/m^3)	623
Thermal conductivity, λ (W/m-K)	0.1879
Specific heat, C (J/kg-K)	831.0
Water absorption, (%)	73
Compressive strength, σ (N/mm2)	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 pugmill) • **Shaping**: Soft mud moulding • **Drying**: Artificial drying using fans • **Firing**: Bricks are fired in an 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	
Bulk density, ρ (kg/m³)	1798
Thermal conductivity, λ (W/m-K)	0.6414
Specific heat, C (J/kg-K)	918.5
Water absorption, (%)	14
Compressive strength, σ (N/mm2)	26.17

Datasheet 42

General information	
Sample type	Handmoulded 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 an 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	
Bulk density, ρ (kg/m³)	1819
Thermal conductivity, λ (W/m-K)	0.7383
Specific heat, C (J/kg-K)	978.6
Water absorption, (%)	13
Compressive strength, σ (N/mm2)	25.8

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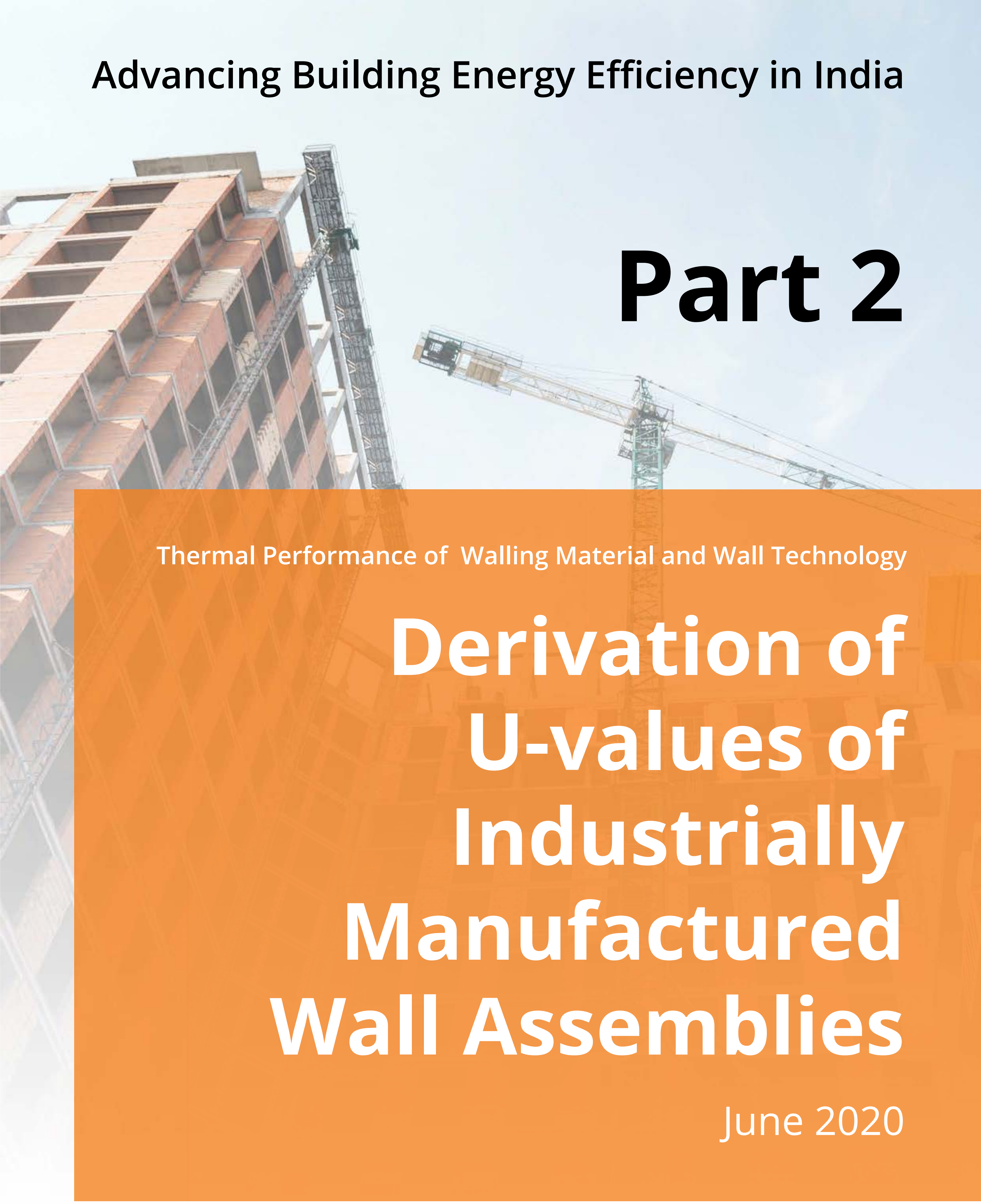

Part 2

Thermal Performance of Walling Material and Wall Technology

Derivation of U-values of Industrially Manufactured Wall Assemblies

June 2020

SHAKTI SUSTAINABLE ENERGY FOUNDATION

CRDF CEPT RESEARCH AND DEVELOPMENT FOUNDATION

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Advancing Building Energy Efficiency in India

Thermal Performance of Walling Material and Wall Technology

Part 2: Derivation of U-values of Industrially Manufactured Wall Assemblies

June 2020

CEPT Research and Development Foundation,
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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 particle
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

Nomenclature

RH	Relative Humidity
U-Value	Thermal transmittance value (W/m^2 K)

INTRODUCTION

The use of various wall construction technologies that promise speed and cost efficiency is being increasingly promoted in India with the boom in the construction of affordable housing. Their thermal performance is an unanswered question in the context of sustainable buildings for the nation's climate action commitments. This report submitted by CRDF, CEPT University aims to facilitate knowledge regarding thermal performance evaluation of such wall construction technologies in practice through the derivation of their U-values, using its state-of-the-art laboratory facilities. This research activity covers around ten wall assemblies that are non-homogeneous and industrially manufactured such as glass, fibre, reinforced concrete walls, EPS based wall systems, etc., along with conventional brick masonry walls. This database has been envisaged to facilitate efficient and sustainable affordable housing construction.

The main objective of this research project is to facilitate knowledge regarding affordable wall construction technologies with reference to their thermal performance. 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.

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 activity.
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

2.1. 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 2 is a photograph showing the assembly of GHB at CARBSE. The testing procedure is further elaborated in Section 5 of this report.

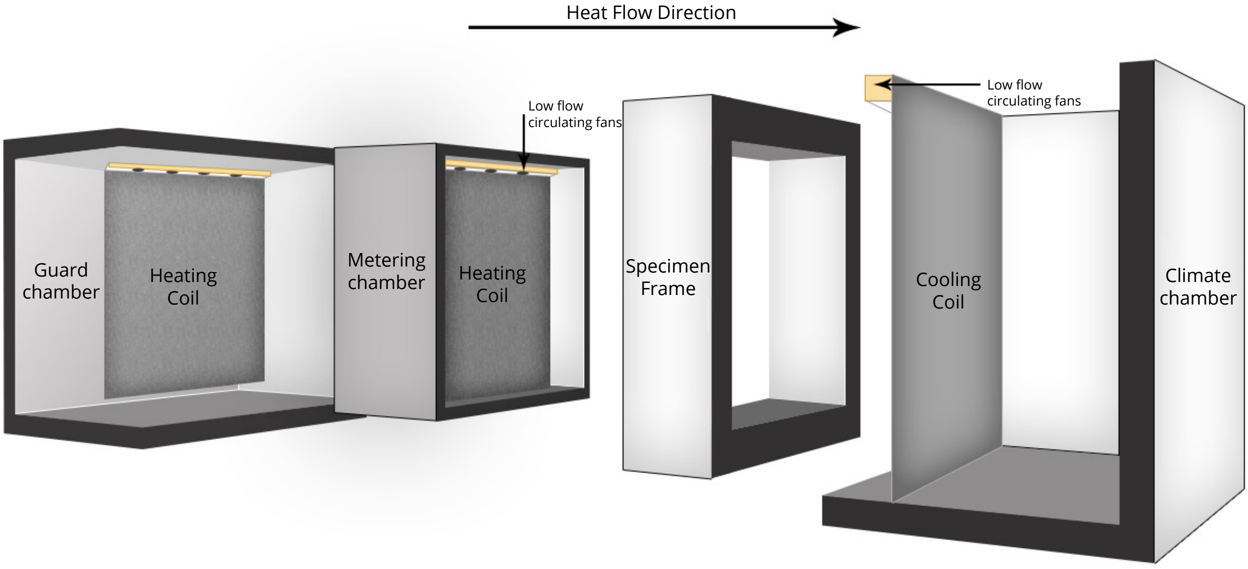
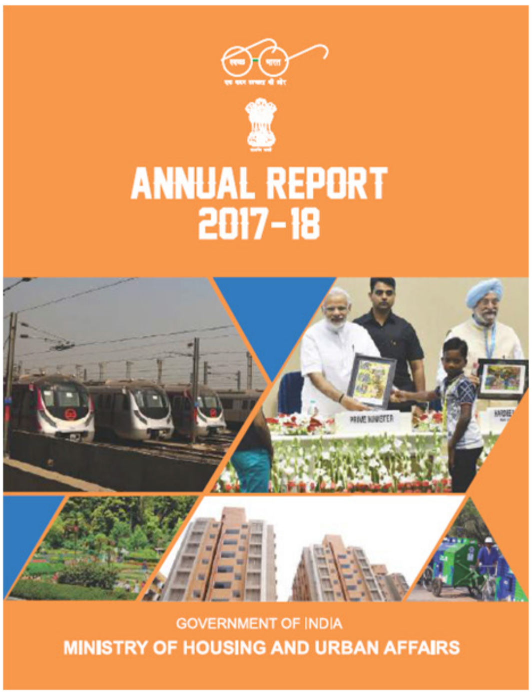


Figure 2: Exploded view of the Guarded Hot-Box apparatus

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

To comply with the main objective of this research project, the wall assemblies that were identified are certified by the Building Materials and Technology Promotion Council (BMTPC), and approved by Pradhan Mantri Awas Yojana (PMAY). 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 4 shows the cover pages of all the 3 compendiums released so far.

Figure 4: Cover pages of 3 different editions of BMTPC Compendium of Prospective Emerging Technologies for Mass Housing
Source: (BMTPC, n.d.-a)



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 5: 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)

Furthermore, the Annual Report 2017-2018 published by Ministry of Housing and Urban affairs under Pradhan Mantri Awas Yojana – Housing for All (Urban) Mission, 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 5 (MOHUA, 2017).

3.1. Sampling Criteria

With the aim to cover the most trending technologies, enabling possible interventions at the earliest, i.e. industrially manufactured and pre-fabricated or pre-cast walling assemblies, the following criteria was set:

1. Availability of Performance Appraisal Certificate (PAC) for the technology.
2. The wall assembly is non-homogenous by nature i.e., avoiding monolithic concrete based assemblies as U-values of common building materials are known.
3. The product/wall assembly is used for external wall applications only, as those are exposed to the outer environment.
4. Availability of the product for procurement from the manufacturers.
5. 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.
6. 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.

3.2. Selected Walling Technologies

Non-homogeneous and low-cost masonry construction techniques/technologies, such as Rat trap bond wall and the standard brick wall, were also tested 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. As observed in Table 1, there are 7 BMTPC certified technologies and 2 masonry construction walls selected under part1 of this research activity. See Annexure 1 for literature and Annexure 2 for drawings of the selected samples.

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

Sr No.	Technologies	No
1	Rattrap bond wall	1
2	Light Gauge framed steel structure with EPS	1
3	Light Gauge framed steel structure with PPGI Sheet	1
4	Reinforced EPS core Panel system	1
5	Glass fibre reinforced Gypsum Panel - Unfilled	1
6	Glass fibre reinforced Gypsum Panel - with RCC and non-structural filling	1
7	Glass fibre reinforced Gypsum Panel - with RCC filling	1
8	Structural stay-in-place formwork system (Coffor) - Insulated panel	1
9	Standard Brick Wall	1
	Total	**9**

PROCUREMENT OF SAMPLES 4

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.

Table 2: Manufacturer information and PAC number of all the selected wall assemblies.

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	-

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

5.1. General Procedure

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

To determine the net energy flow through the specimen, a fivesided 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 specimenat 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 6 (ASTM, n.d.).

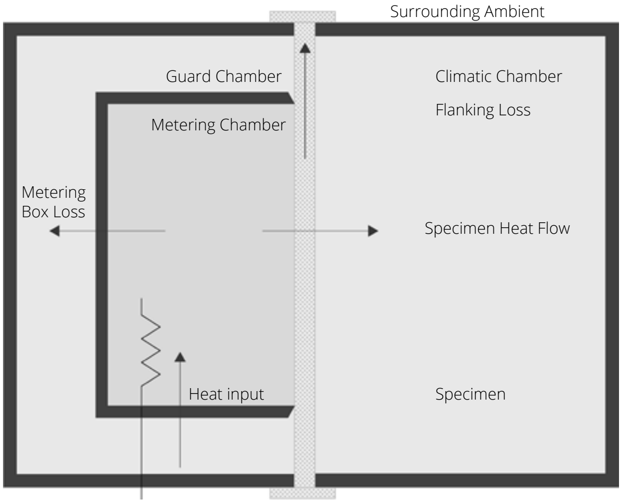


Figure 6: Sectional illustration of the Guarded Hot Box (GHB) apparatus

Figure 7: Photographs showing thermal imaging (left) and testing of Rattrap bond wall assembly in GHB

5.2. 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 7.

5.3. 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 8.

Figure 8: Photographs showing sealing procedure with XPS (left) and silicone sealant (right) to avoid heat transfer through gaps

Table 3 shows the U-values obtained for the nine tested wall assemblies and Figure 9 shows evaluation of the thermal performances of the same.

Table 3: U-value database of the selected walling technologies

Sr No.	Wall types	No	U value (W/m².K)
1	Rattrap bond wall	1	1.673
2	Light Gauge framed steel structure with EPS	1	1.188
3	Light Gauge framed steel structure with PPGI Sheet	1	1.629
4	Reinforced EPS core Panel system	1	0.907
5	Glass fibre reinforced Gypsum Panel - Unfilled	1	1.559
6	Glass fibre reinforced Gypsum Panel - with RCC and non-structural filling	1	1.715
7	Glass fibre reinforced Gypsum Panel - with RCC filling	1	1.534
8	Brick Walll	1	1.670
9	Structural stay-in-place formwork system (Coffor) - Insulated panel	1	0.52
	Total	**9**	

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

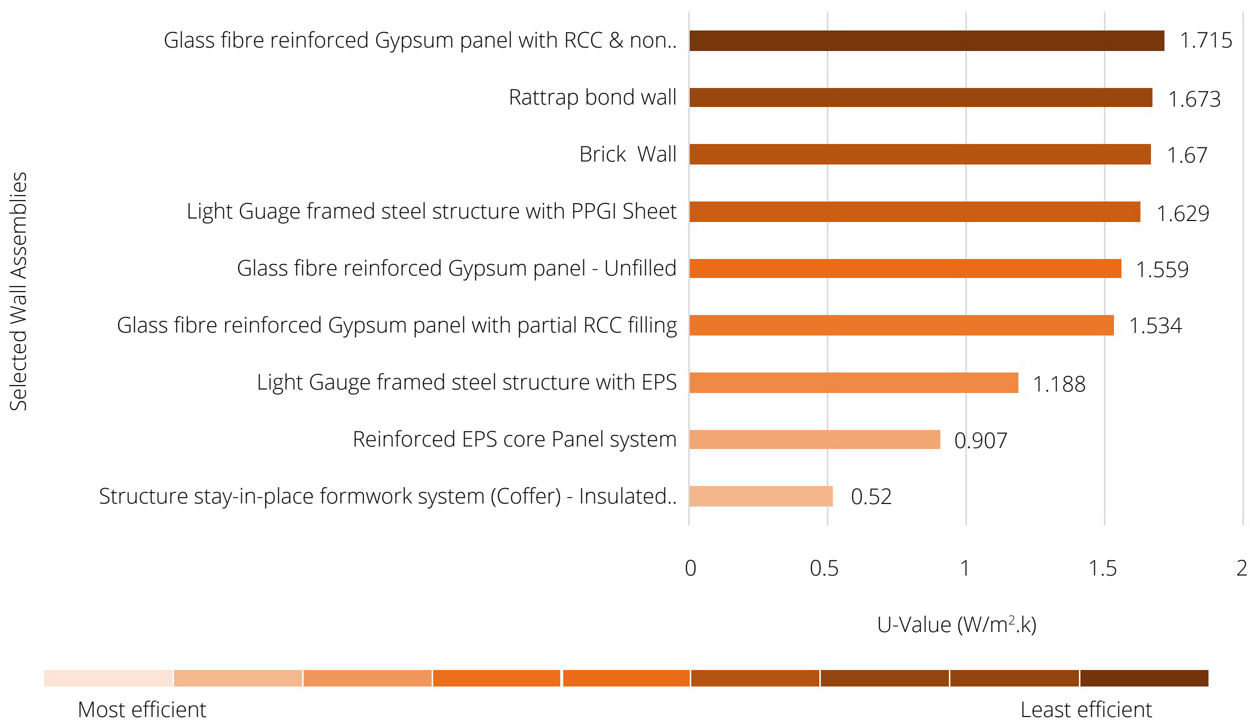


Figure 9: Thermal performance evaluation of the selected wall assemblies

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ANNEXURE 1: 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. As per a case study conducted to assess the cost effectiveness of Rat trap bond wall constructions in India, 26% of the material and labour costs can be saved (Tam, 2011). 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 230mm thick and the bricks are laid as shown in Figure 11, with different brick faces (Shiners and Rowlocks) to form a cavity unlike conventional brick laying (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 230mm 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
Source: (Saurabh, 2015)

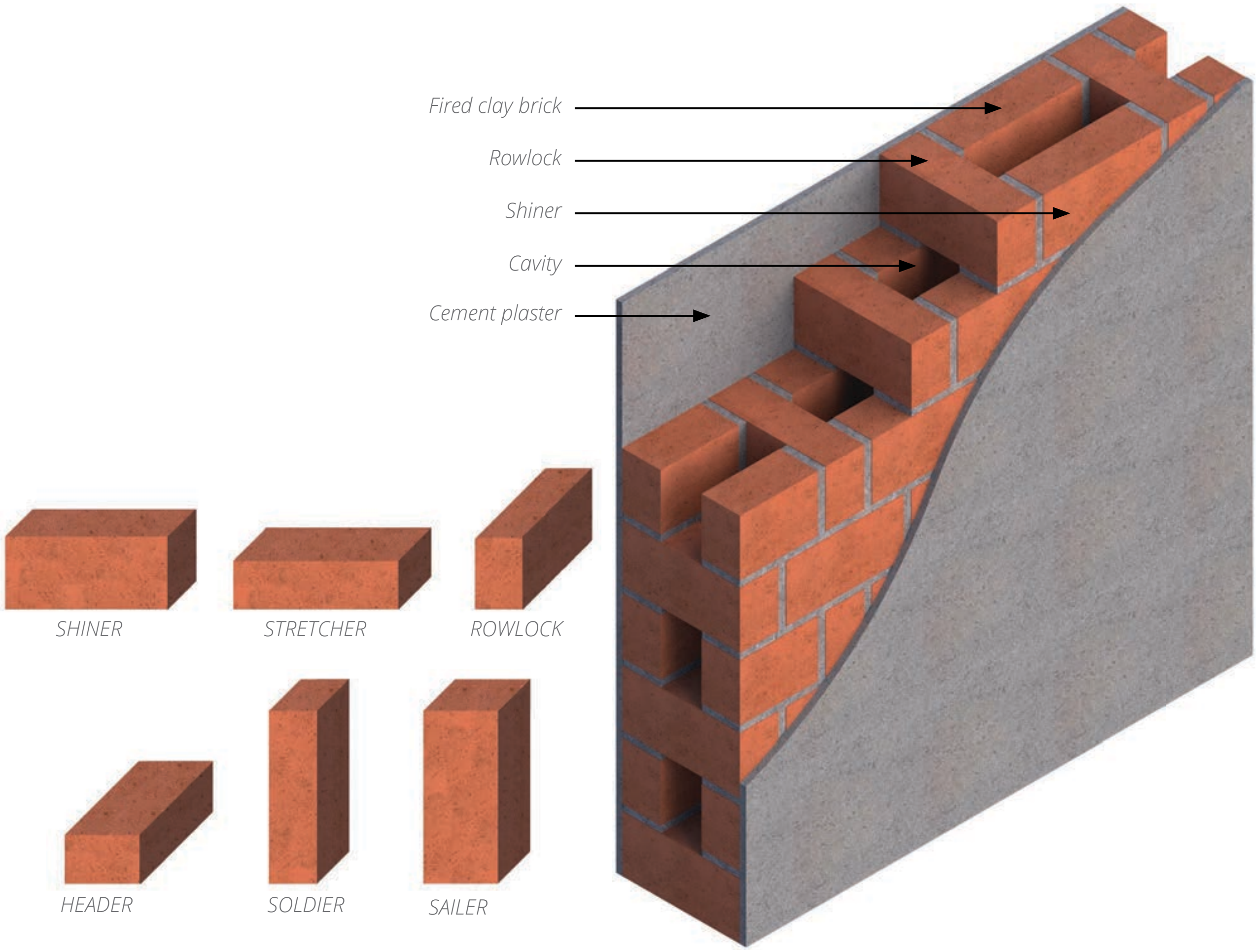


Figure 11: Different brick faces used in wall construction (left) and 3D illustration of a typical Rat-trap bond Wall (right).

Figure 12: Photograph 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 in Figure 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 shotcreteas its external layers as illustrated in Figure 14. Figure 16 shows the test sample acquired from the manufacturer mentioned in Table 2 and fixed into the GHB specimen frame.

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, as illustrated in Figure 15. 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 1.

Figure 13: Photograph showing walls and floor plates of LGFSS assembled at a site. Source: (BMTPC, 2018b)

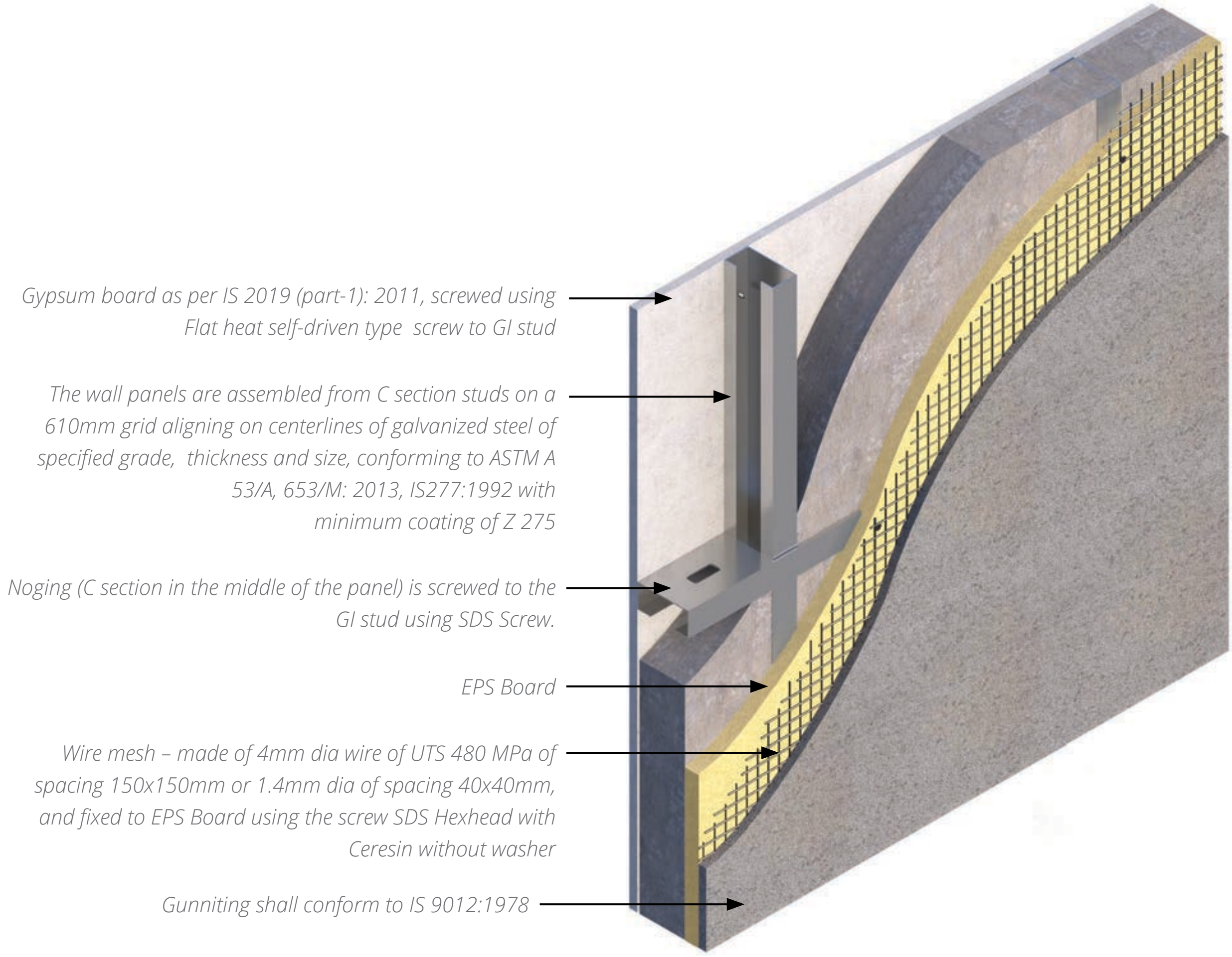


Figure 14: 3D illustration of LGFSS - EPS with specifications

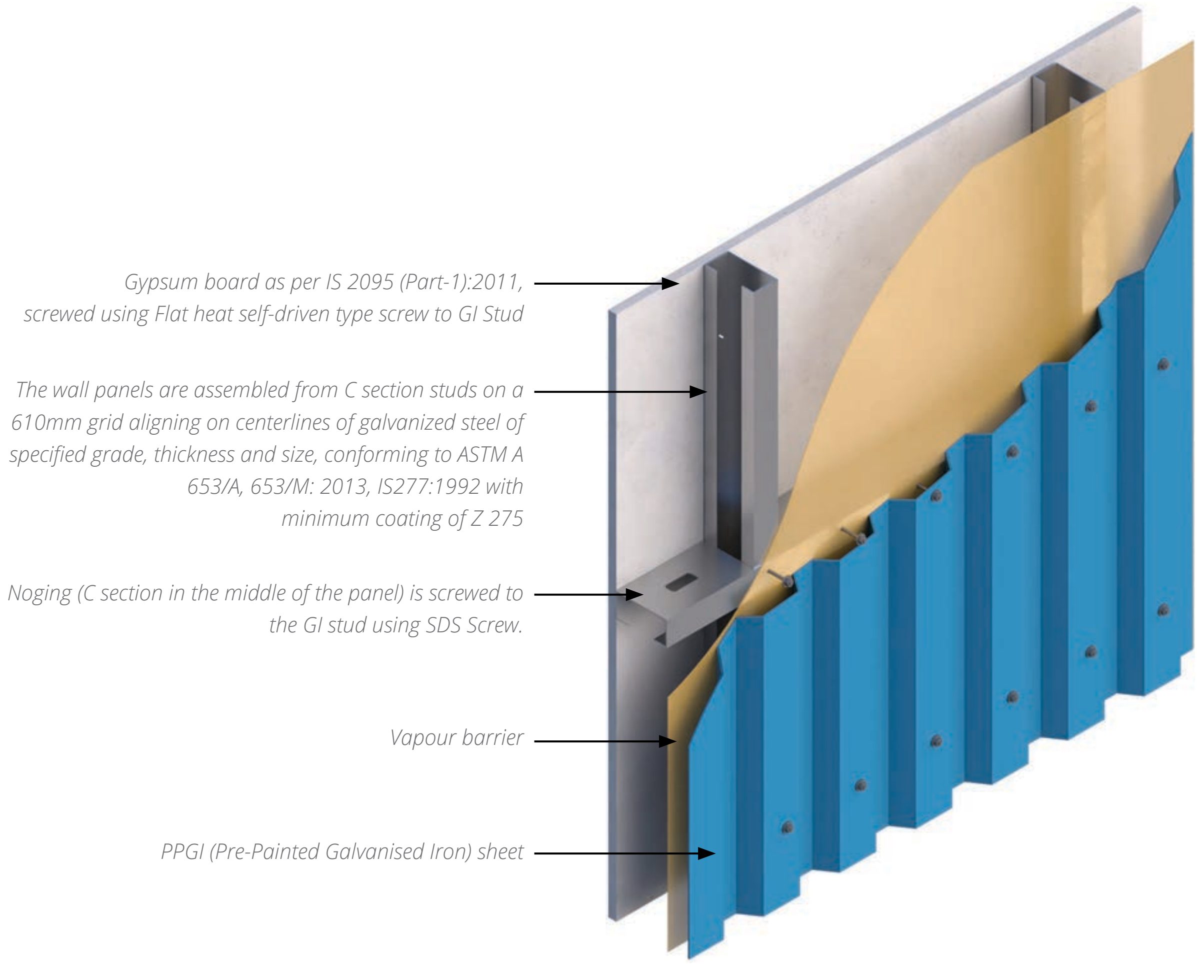


Figure 15: 3D illustration of LGFSS – PPGL sheet with specifications

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

Figure 17: Photograph of LGFSS with PPGL sheet wall sample (left) & the sample installed within 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. The panel consists of an EPS core reinforced with an interconnected framework of zinc-coated wire mesh as illustrated in Figure 18. 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) as seen in Table 2.

The sample panel was prepared as per established standards by the manufacturer. The sample wall panel of size 980mm x 980mm was delivered to CARBSE and directly fixed for testing into the GHB specimen frame as shown in Figure 19. 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)

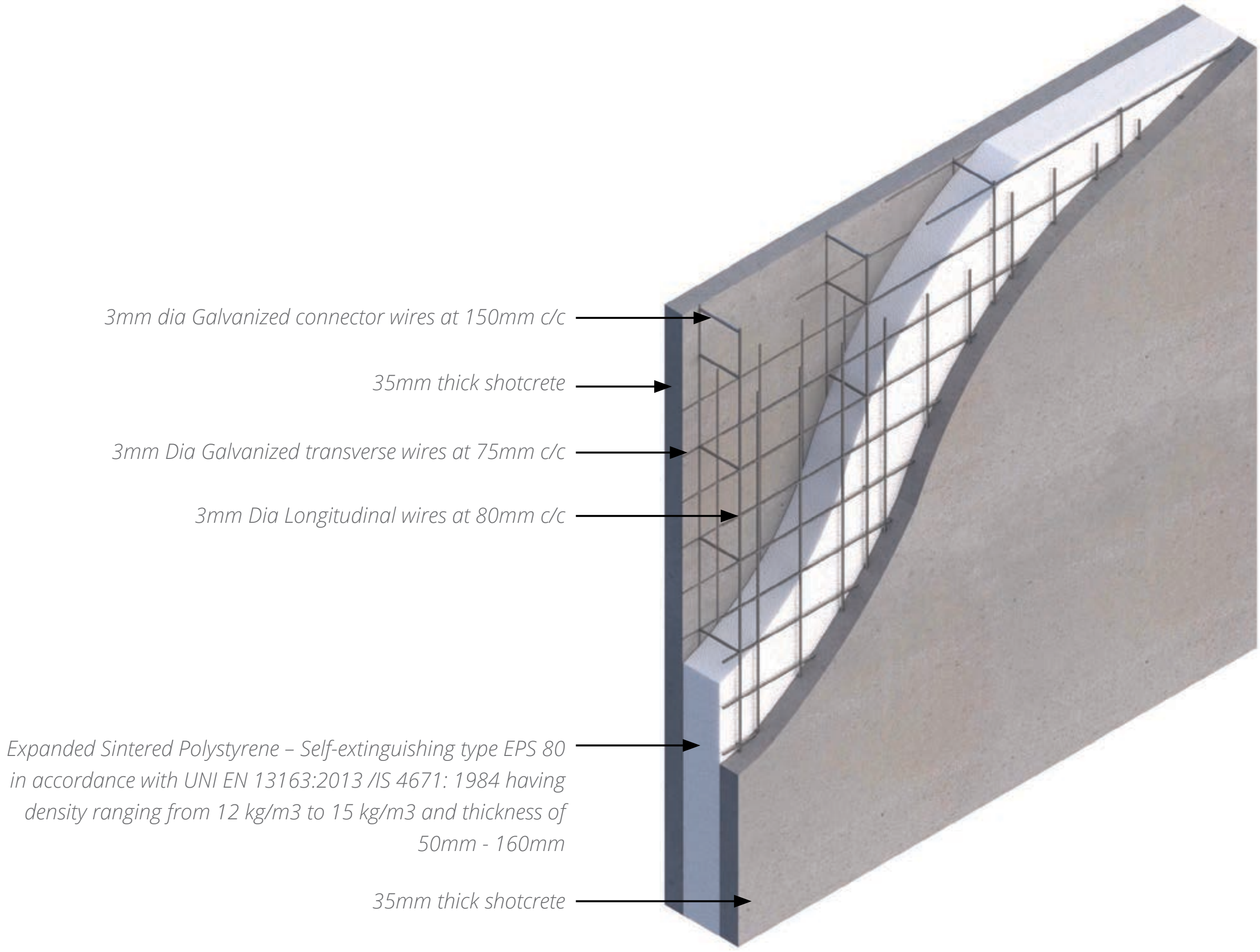


Figure 19: 3D illustration showing specifications of EPS core panel

Figure 20: Example of on-site shotcreting (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)

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 21 and Figure 22. 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 23.

Three samples of GFRG panels were obtained from the manufacturer and were prepared as per standard applications on-site as seen in Figure 23. 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 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) as illustrated. It also shows one of the GFRG panels fixed into the GHB specimen frame. Annexure 2 contains illustrations for the same.

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

Figure: 22: Components of a typical GFRG panel (left) (BMTPC, 2011), on-site preparation of GFRG partly filled panel (middle) and GFRG fully filled panel fixed into the GHB specimen frame (right)

Figure 23: 3D illustrations (left) and photographs of the GFRG Panel samples: unfilled, partly filled and fully filled (right)

5. Brick wall

A conventional brick wall popularly adopted for housing construction in the country, as seen in Figure 24, was also tested as a base case for the purpose of this research. A standard 230mm 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 25. It was tested only after being allowed to dry and being tested for moisture via thermal imaging.

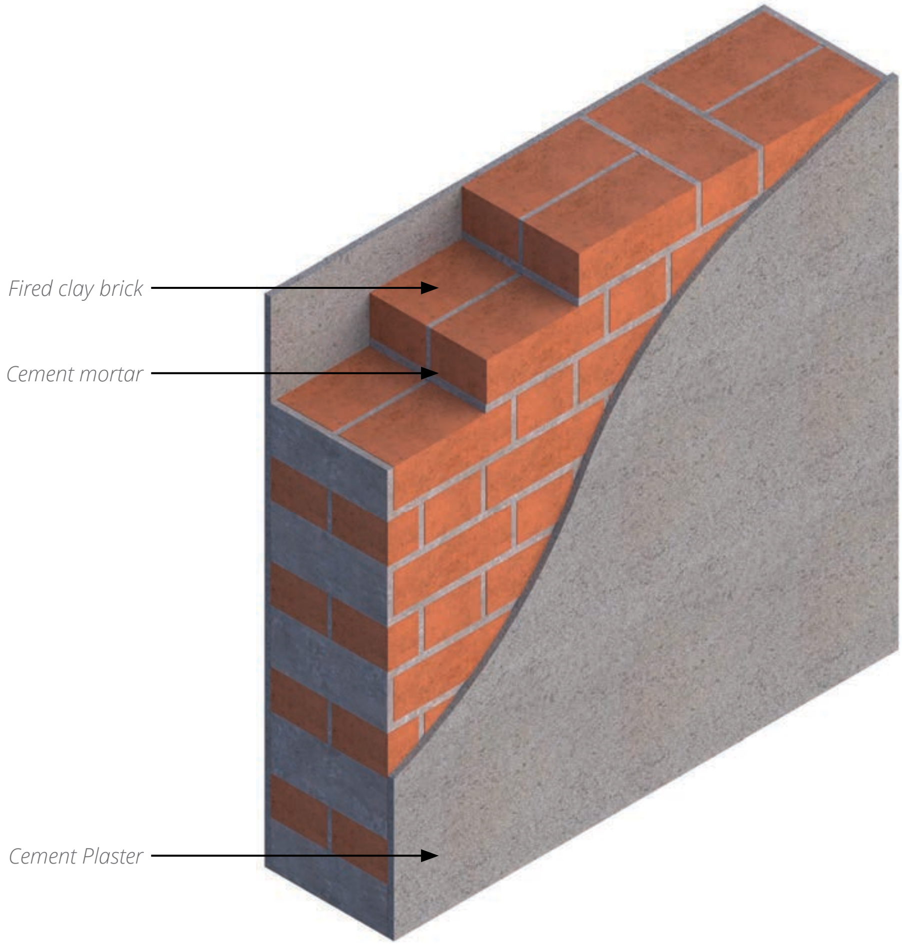


Figure 24: 3D illustration of a conventional brick wall

Figure 25: Photographs showing the 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 26. As illustrated in Figure 27, 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 28, 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 the construction drawings in Annexure 2. Any gaps between the sample and specimen frame were further sealed using XPS insulation strips and finally sealed using silicone sealant, as shown in Figure 30. The illustration in plan and elevation is available in Annexure 2.

Figure 26: Photographs of the assembly of 'Coffor' panels without insulation (first) and filled with concrete on-site (second). Source: (Coffor Construction Company LLD, n.d.)

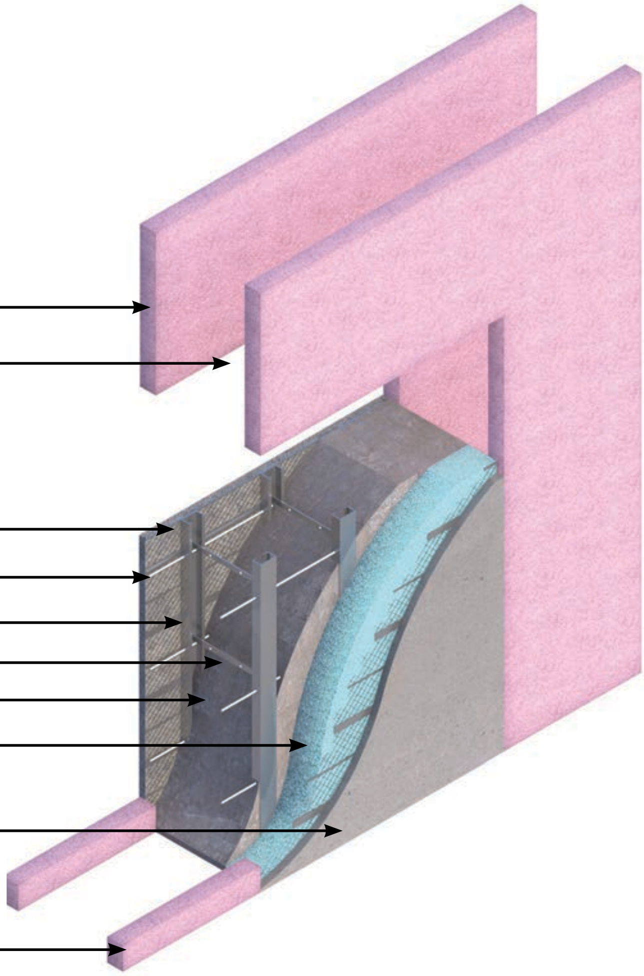


Figure 27: 3D sectional illustration of insulated coffor panel sample used as the specimen for the test.

Figure 28: Photograph of an insulated coffor panel sample without concreting (left), Photograph of concrete poured in-situ in the insulated coffor panel sample (right).
Source: (left) (BMTPC, 2018c)

ANNEXURE 2: SCHEMATIC DRAWINGS OF THE TEST SAMPLES

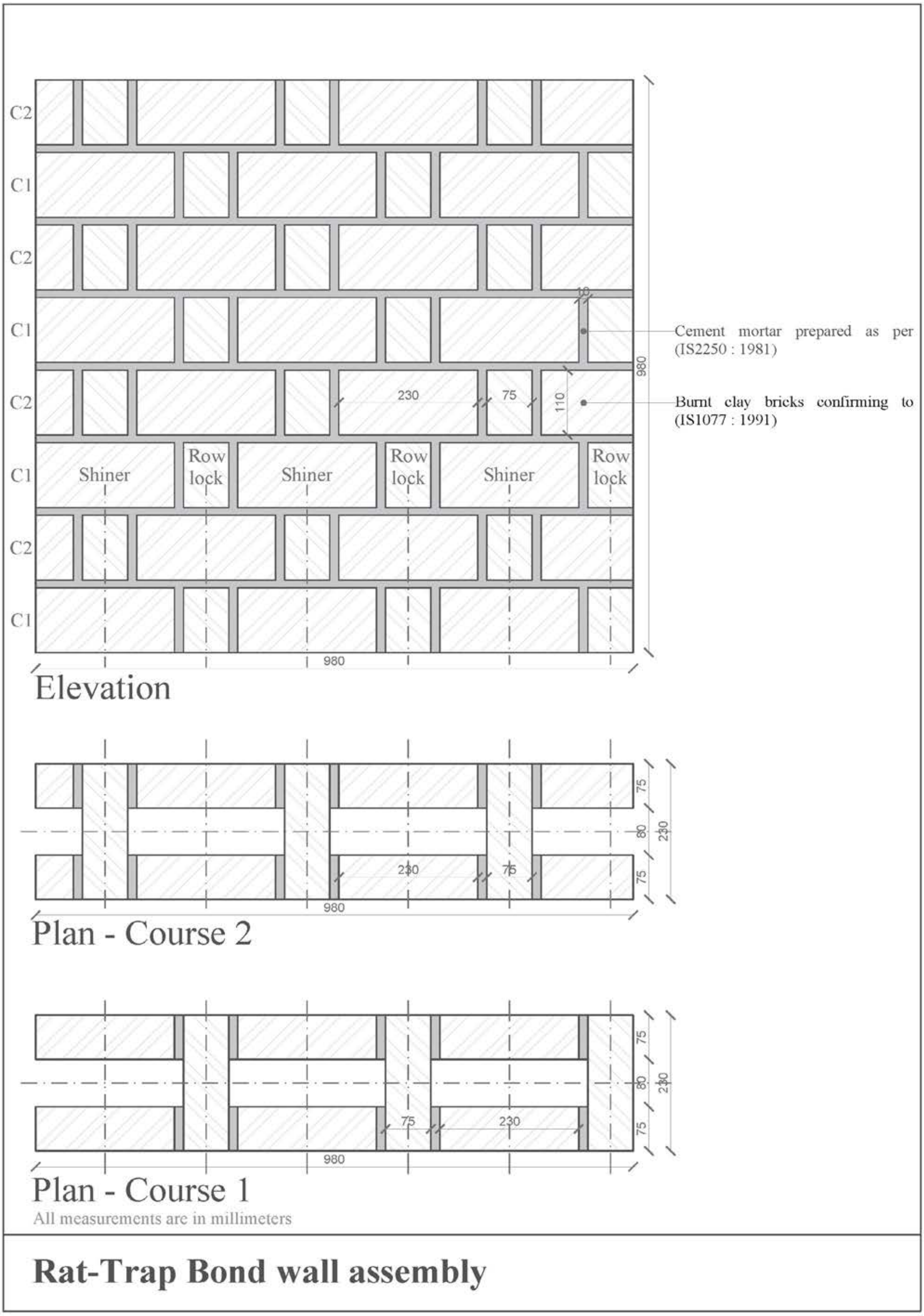


Figure 29: Schematic plans and elevation of Rat-trap bond wall.

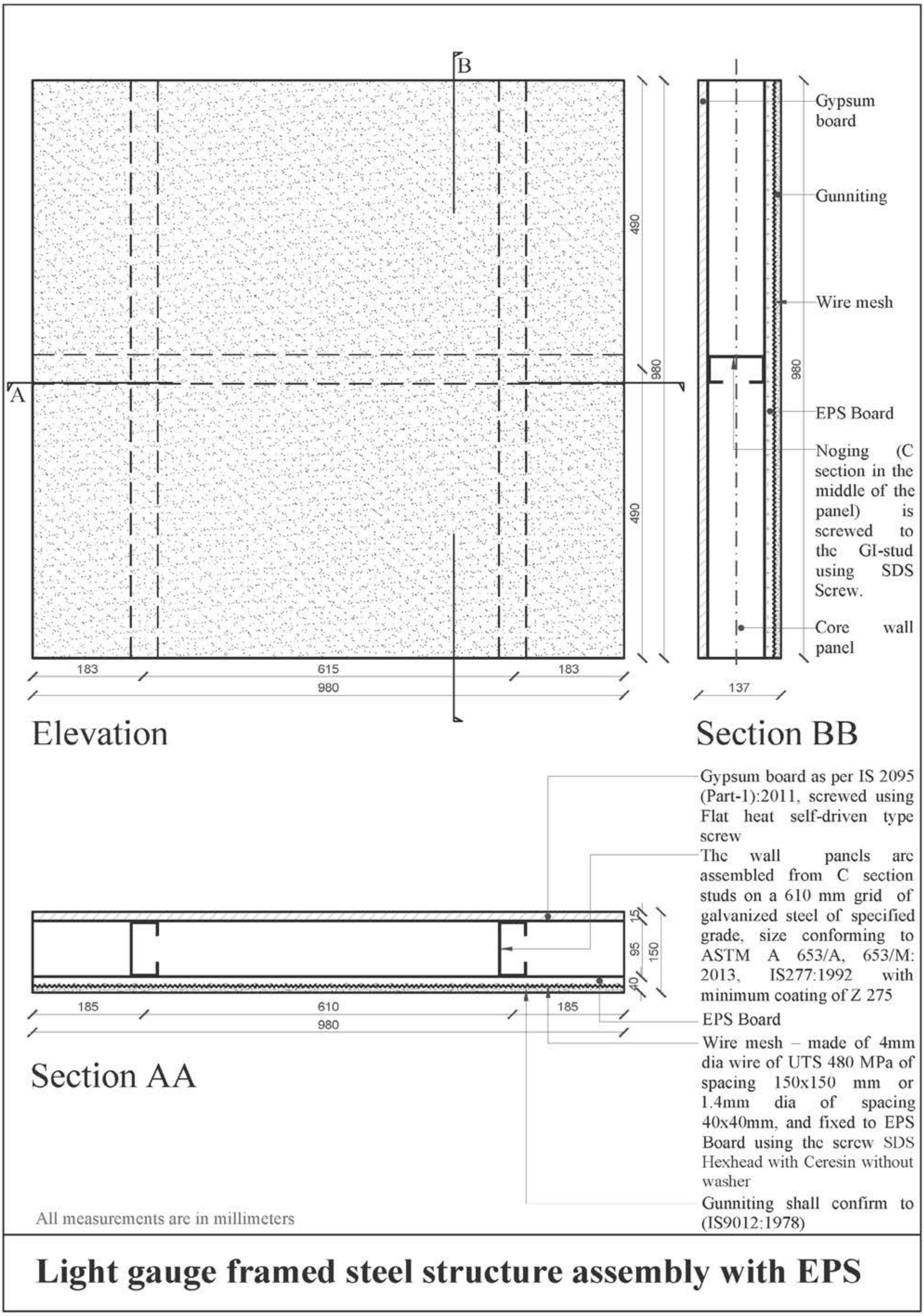


Figure 30: Schematic drawings of light gauge framed steel structure wall sample: External wall type 1 with EPS as per specifications and drawings found in BMTPC Performance appraisal certificate (PAC) no: 1014-S/2014.

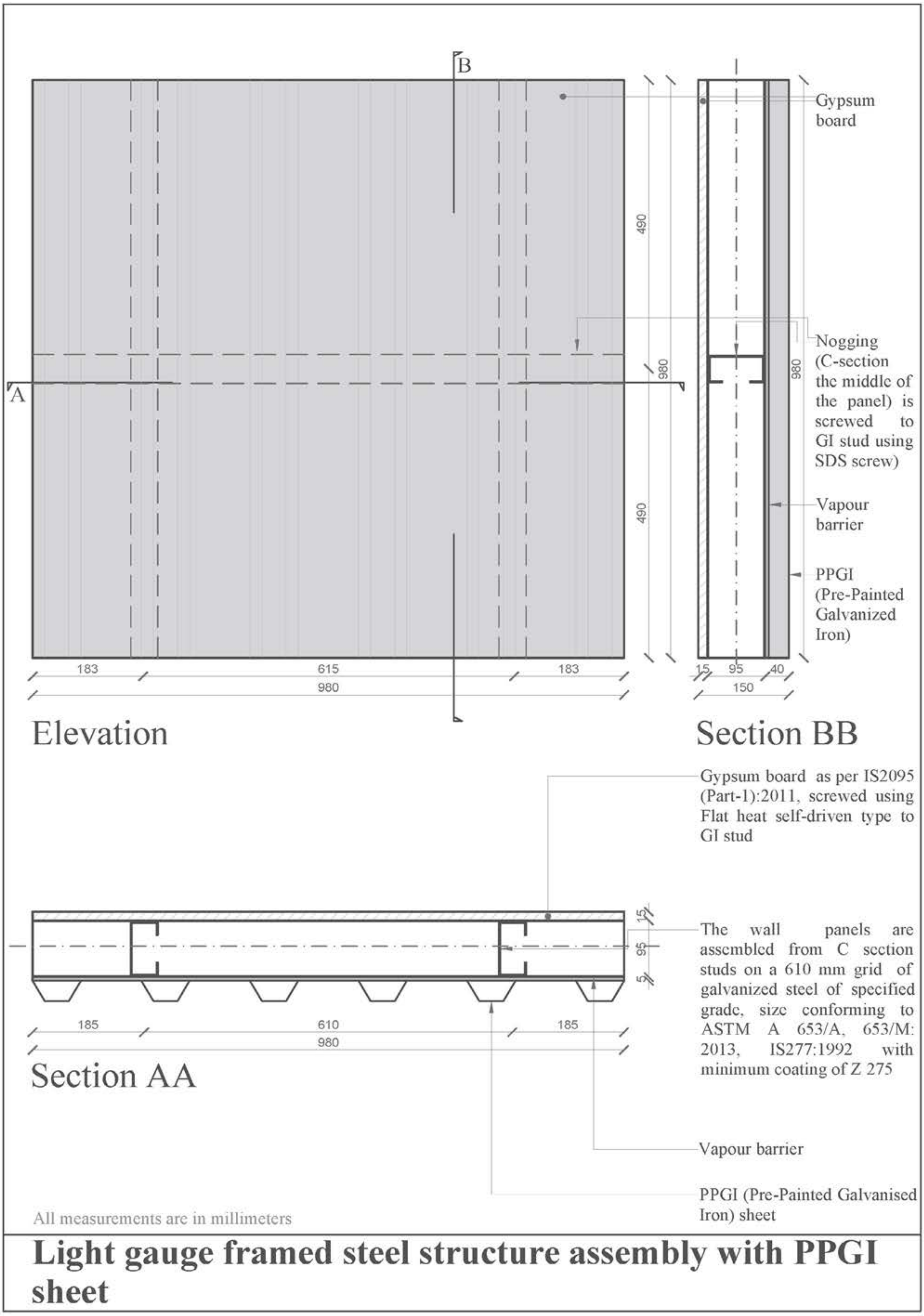


Figure 31: Schematic drawings of light gauge framed steel structure wall sample with PPGI sheet as per specifications and drawings found in BMTPC Performance appraisal certificate (PAC) no: 1014-S/2014.

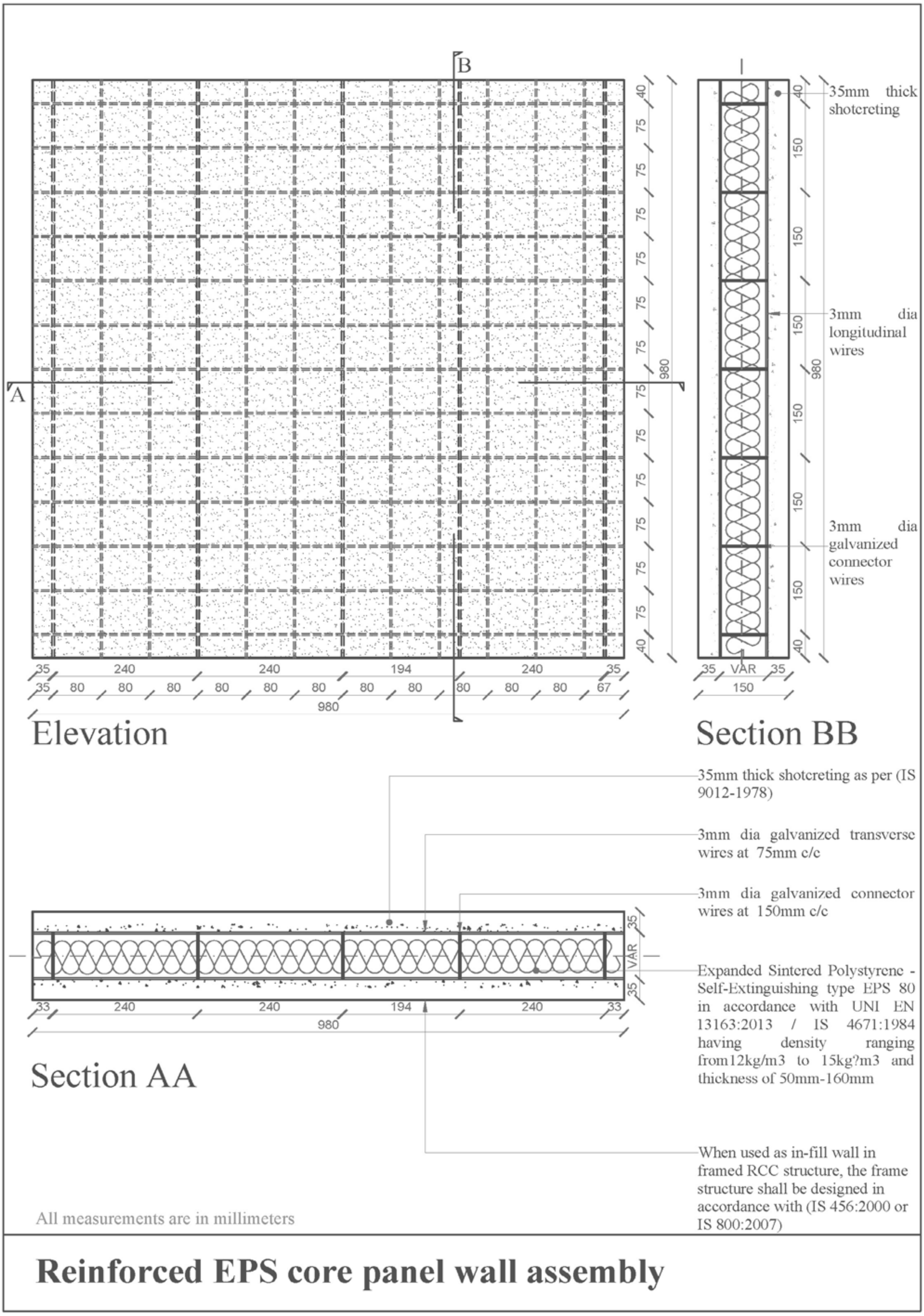


Figure 32: Schematic drawings of Reinforced EPS core panel wall sample as per specifications and drawings found in the BMTPC Performance Appraisal Certificate (PAC) no: 1020-S/2015.

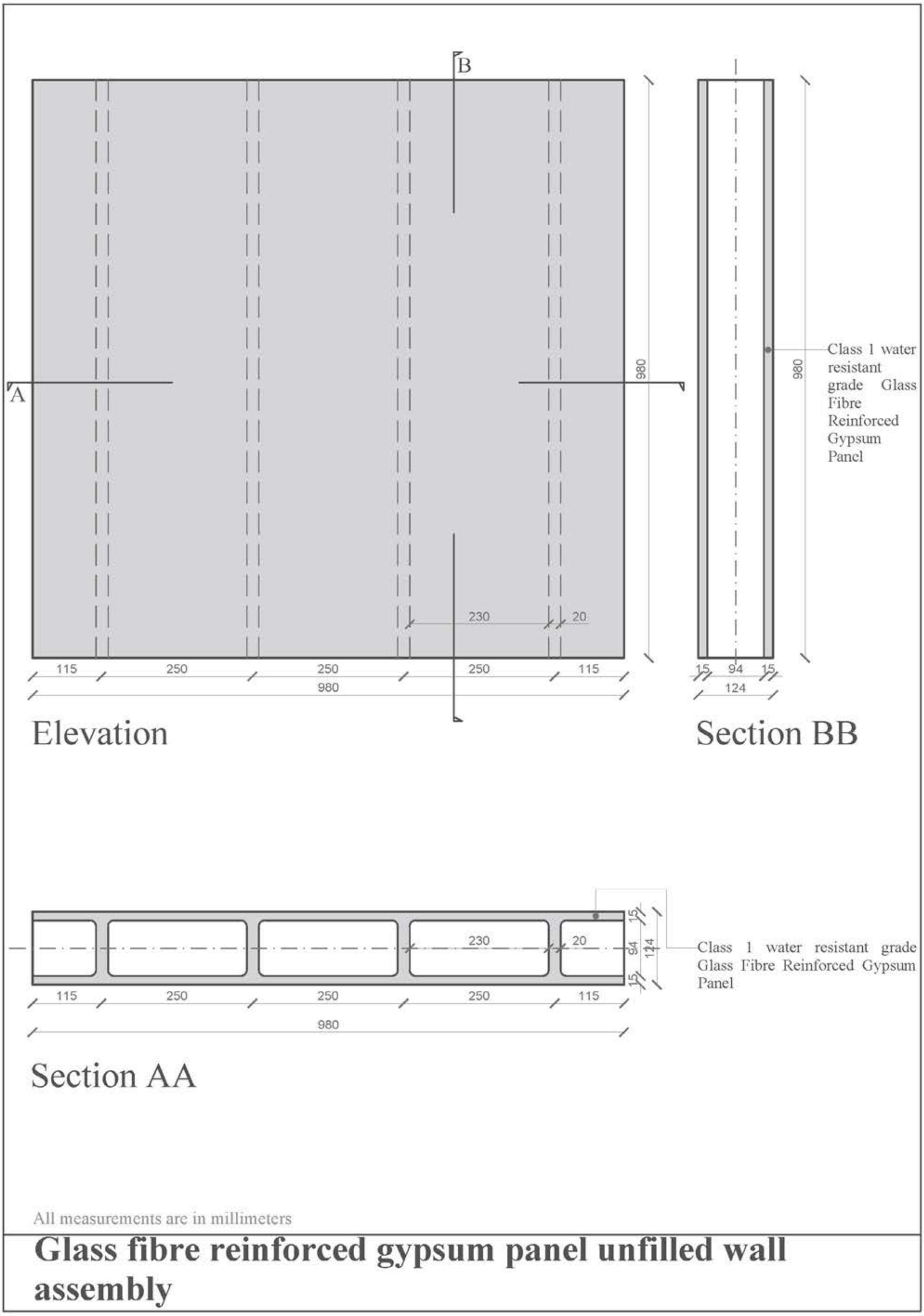


Figure 33: Schematic drawings of Glass Fibre Reinforced Gypsum building Panel wall sample; Class-1 unfilled panel, as per specifications and drawings found in BMTPC Performance Appraisal Certificate (PAC) no: 1009-S/2012 and structural design manual.

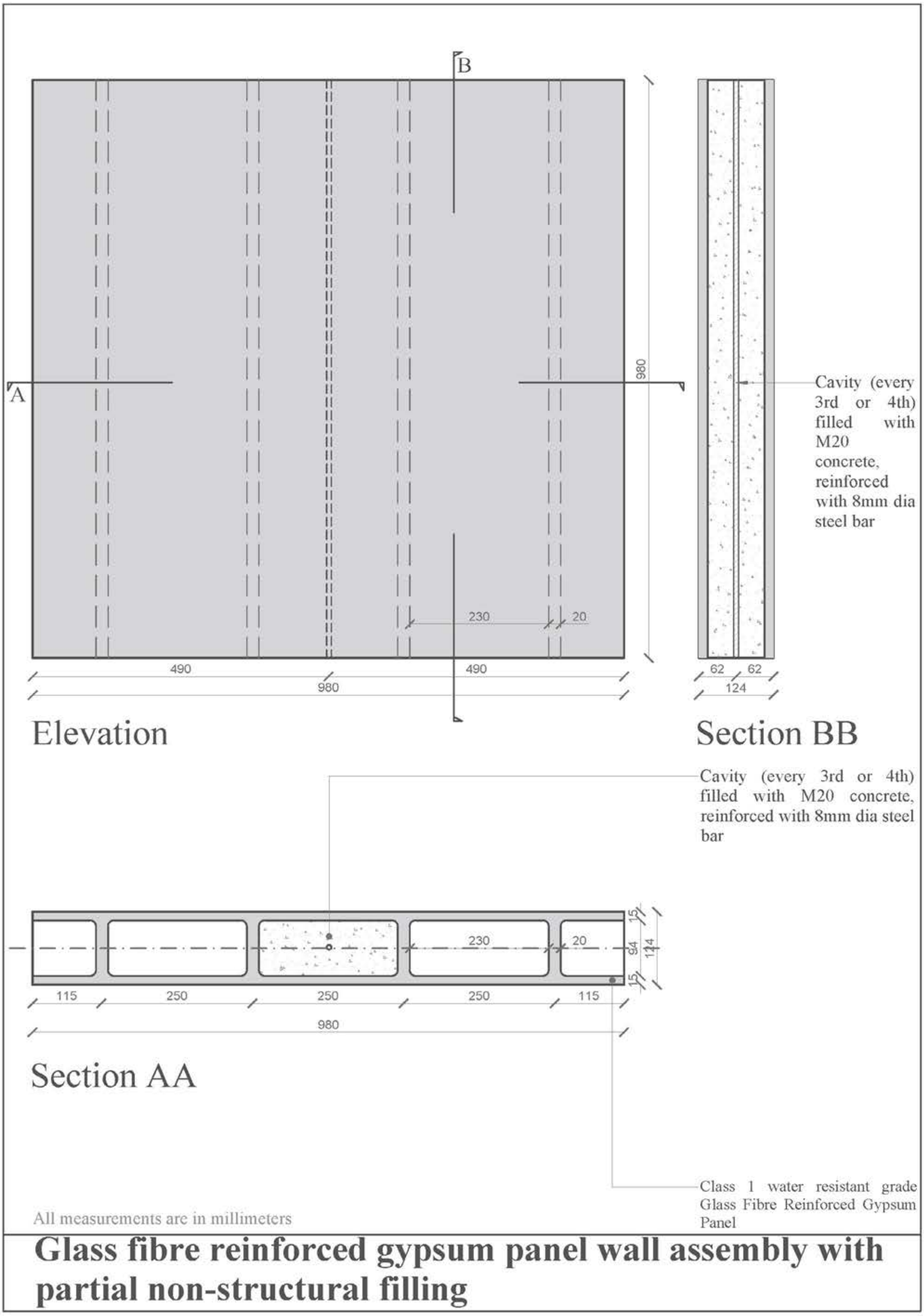
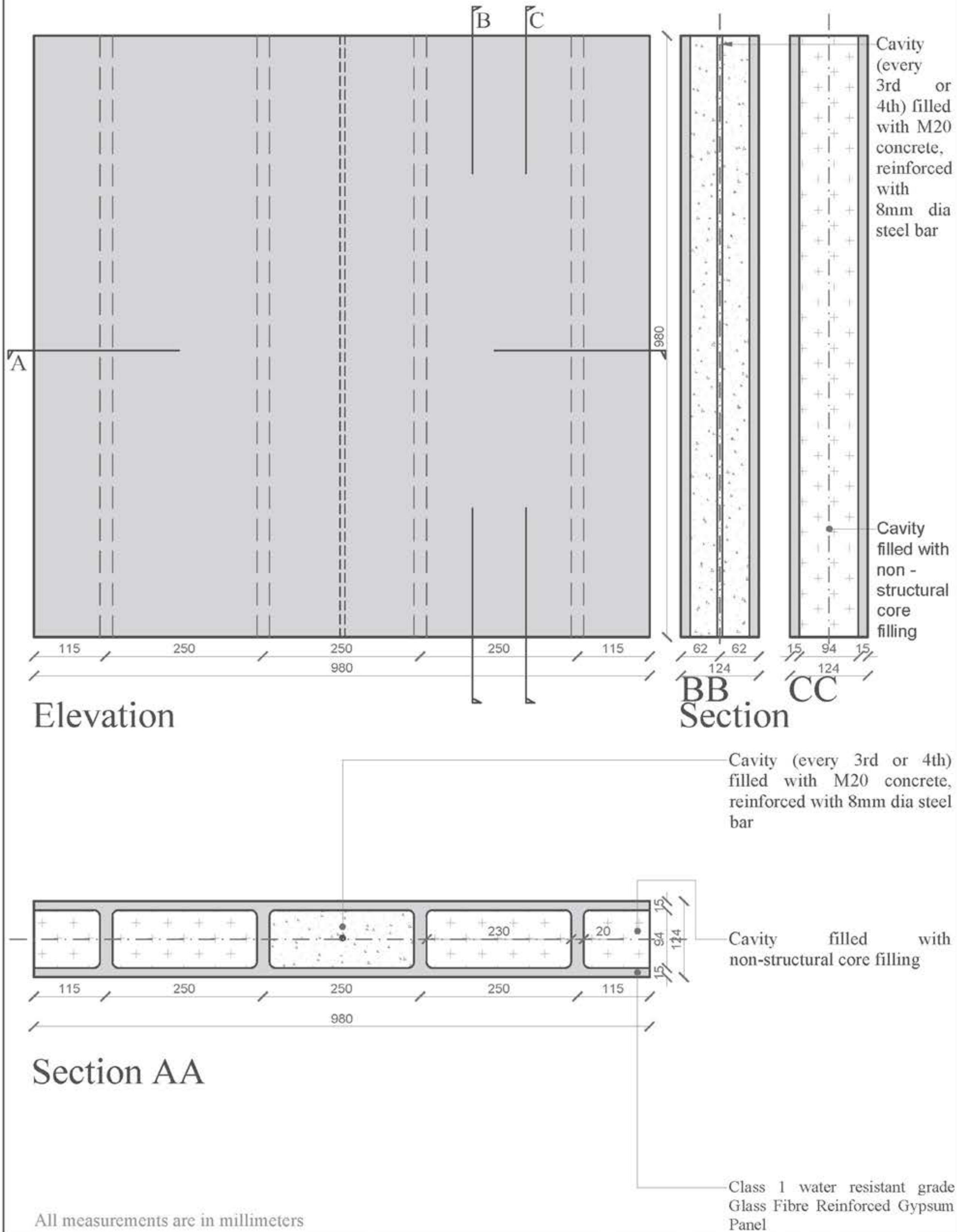


Figure 34: Schematic drawings of Glass Fibre Reinforced Gypsum building Panel wall sample; Class-1 partially filled load-bearing panel with non-structural core filling as per specifications found in BMTPC Performance Appraisal Certificate (PAC) no: 1009-S/2012 and structural design manual.



Glass fibre reinforced gypsum panel partially filled wall assembly

Figure 35: 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 manual.

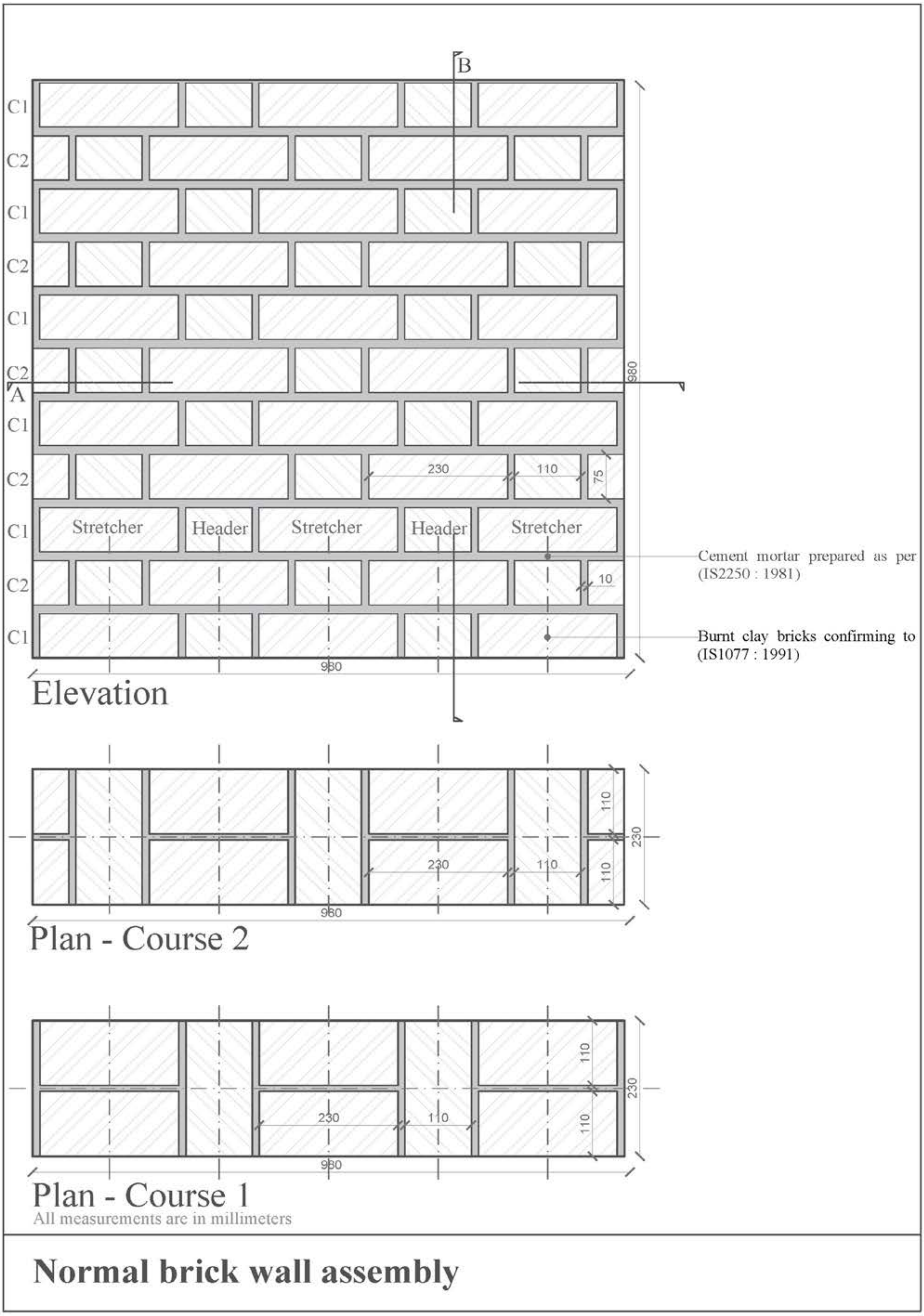


Figure 36: Schematic plans and elevation of the standard brick wall.

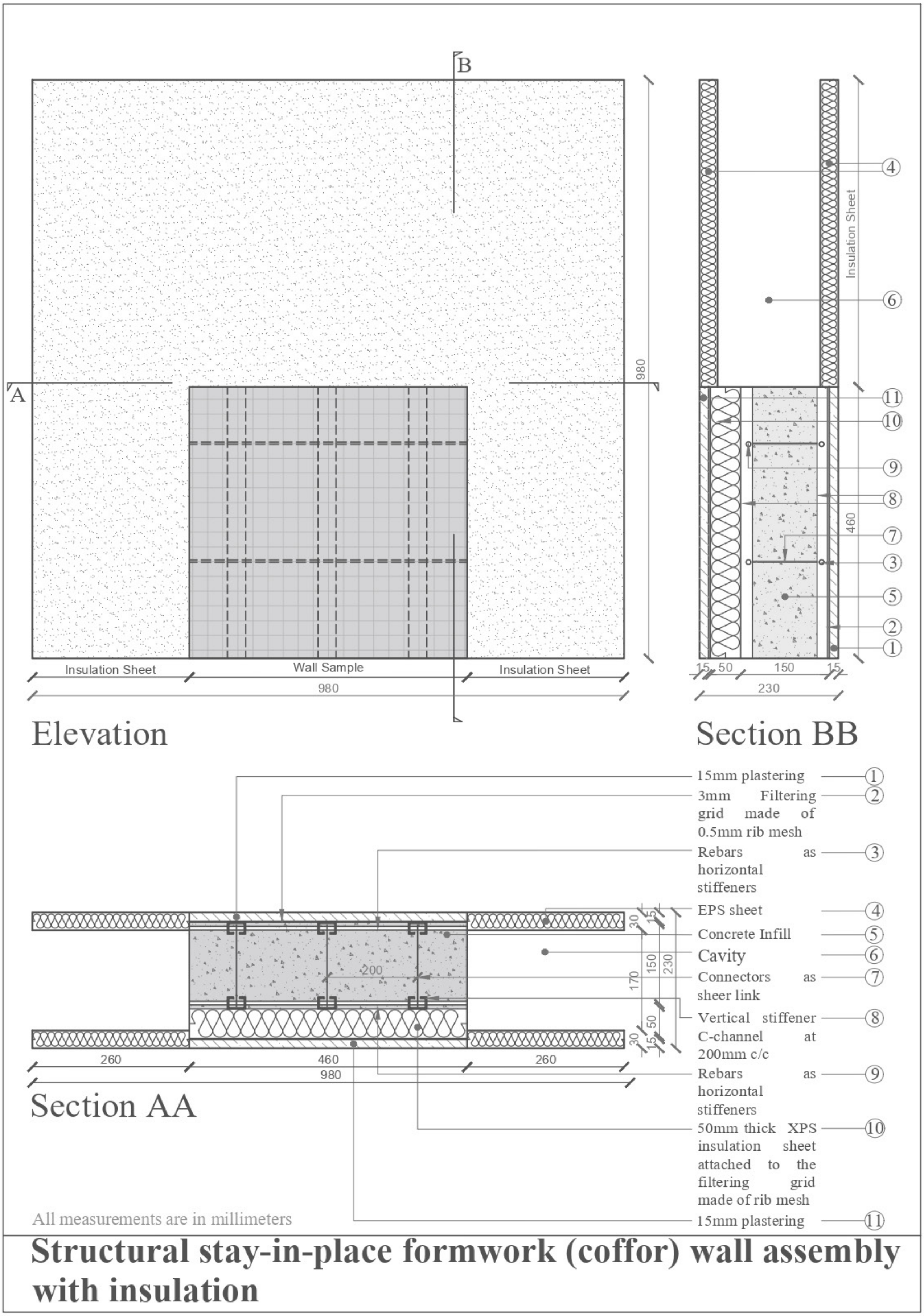


Figure 37: Schematic drawing of Structural Stay-in-Place Formwork (Coffor) wall sample with insulation as per specifications found in BMTPC Performance Appraisal Certificate (PAC) no: 1035-S/ 2018.

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