Thermal Characterization and Performance Evaluation of Straw Fiber Reinforced Mud Block

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Abstract

This study presents the characterization of the thermal properties of straw fiber stabilized mud block [SMB] and evaluates the thermal performance of building envelopes to moderate the indoor temperature. 0.1% to 0.2% of straw fiber and 5%-7.5% cement was mixed with the soil to prepare 5 different types of samples for thermal characterization. The findings show that the addition of 0.2% of straw fiber reduces the thermal conductivity coefficient (k) by 43% and improves the thermal resistance of earthen building envelopes by 76% while decreasing their density (ρ). The experimental outcomes were used to simulate the thermodynamic behaviors of a single-story residential building using Energy-Plus software to understand the effect on indoor comfort indicators such as mean radiant temperature (MRT), air temperature (AT), and operational temperature (OT) by changing the exterior wall material with locally available materials. The result demonstrates that during the outdoor peak temperature at 3 pm, the mud block wall can decrease the indoor temperature up to 2.18 °C which is the lowest among all the conventional buildings. During the indoor pick at 7 pm, the temperature of the mud block house is 1.67 °C, 1.47 °C, and 2.31°C less than brick, concrete, and Corrugated Galvanized Steel (CGS) sheets respectively. The result shows that SMB houses offer more comfortable living conditions and are better suited for naturally ventilated houses.

Keywords: Energy plus Simulation, Stabilized Mud Block, Straw Fiber, Thermal Performance, Thermal Properties

1. Introduction

The construction industry is making progress in adopting more environmentally friendly and sustainable building practices. At present, the interest in developing new building materials that are eco-friendly and have improved thermal properties for constructing building envelopes is amplifying hugely [1]. When the heat storage capacity of the building's structure decreases, it can lead to instability in indoor surface temperatures, especially in environments with significant variations in external temperatures and solar radiation [2]. As a result, the level of comfort experienced by occupants can be greatly diminished. Traditional materials like fired bricks and concrete blocks which are the most used building materials in Bangladesh have a high embodied energy requirement due to the intense heat needed to achieve the desired strength, leading to excessive fuel consumption. To address this issue, scientists are revisiting the use of readily available materials like mud and lime to produce masonry blocks, aiming to reduce fuel consumption [3].

Mud has been used as a building material since 2500 BC due to its affordability, availability, and suitable thermal properties [4]. In Bangladesh, the history of earthen structure construction is over 200 years old. Some large districts of Bangladesh such as Rajshahi, Khulna, Potuakhali, Dinajpur, Bogura, and Chittagong are the common areas where handmade adobe blocks and rammed mud wall is widely constructed using straw fibers and cow dung as a stabilizer [5]. However, their brittleness, low compressive and tensile strength, and affinity with water make them less desirable compared to other commonly used materials. For six decades noteworthy research has been conducted to make unfired stabilized bricks to be a sustainable alternative to bricks and concrete blocks [6]. Many research studies reported on improvement of compressive strength and on enhancing bond characteristics with the addition of fibers in soil masonry which can reduce the wall width and increase the usable interior space [7],[8], [9], [10], [11].

But not much research regarding the effect of straw and other natural fibers on the thermal conductivity coefficient of mud brick is available. The goal of this research is to find the effect of straw fiber on the thermal insulation of SMB and for that, earth block with different percentage of cement and straw fiber were prepared and the thermal conductivity coefficient was measured. For a better understanding of the inter-relationship between thermal conductivity and its impact on lower indoor temperature, a comparative analysis of the thermal performance of SMB and locally available building materials such as CGS sheets, brick, and concrete was conducted. The analysis of the thermal performance of the envelope using parametric studies could be an efficient strategy to achieve indoor thermal comfort for the inhabitants and establish the use of straw-reinforced mud blocks as a successful alternative to fired clay bricks, concrete, and CGS sheet which can have considerable outcomes on conserving the building energy.

2. Materials And Methods

Raw Materials

Soil:

The soil was collected from a riverside place named

Fig. 1 Selected site for soil collection [Source: Google Map]

Fig. 2 Soils collection (a) Riverside soil [site 1] (b) Island soil [site 2]

Table I Sedimentation result of soil sample

Grading	River Bank Soil (%)	River Island Soil (%)
Gravel Fraction	0.0	0.0
Sand	70	95
Clay	16.5	3
Silt	13.5	1

Table II Designation of Mixtures

Sample Designation	Composition of bodies of fibrous mud bricks
A	Traditional Mud-brick (Only soil + water)
B1	Clay + Straw 0.1%+ 5% Cement + Water
B2	Clay + Straw 0.1%+ 7.5% Cement + Water
B3	Clay + Straw 0.2%+ 5% Cement + Water
B4	Clay + Straw 0.2%+ 7.5% Cement + Water

Betagi, located 6 kilometers away from Chittagong University of Engineering and Technology. As soil character is most important for earth blocks, we selected two different sites for soil collection for this experiment. Site 1 is located on the riverbank and site 2 is located on the island in the river. Both soil samples were collected from 1 meter below the ground level. Fig. 1 shows the location of two different sites and Fig. 2 shows the soil collection procedure from the sites. To achieve initial uniform moisture content, the soil collected from both sites was stored at a room temperature of 22 °C and a relative humidity of 65 – 70% for 15 days before preparation and sieving. Sieving was conducted according to ASTM D422-63 Standard Test Method for particle Size. Grain size distribution for both soil samples is illustrated in Table I. The results indicate that for riverbank soil the clay proportion is 16.5% and silt proportion 13.5%, with total siltand clay value being around 30% which is within the recommended limits required for the production of soil blocks [12], [13]. The soil also contains 70% sand by proportion which is sufficient to limit the shrinkage of blocks when drying out [14].

Cement:

Ordinary Portland cement (Clinker 95%-100% and Gypsum 0-5%) was used as binding material. The percentages of stabilizers normally depend on the type of stabilizer but comparing various research it was found that 4-10% cement is added to the dry weight of the soil [15], [16]. Here 5% and 7.5% cement of the total soil was selected and added to the mixes.

Fiber:

Rice straw fibers have better thermal properties than any other natural cellulose fiber collected as an agricultural by-product which is one of the main reasons for its widespread use in traditional mud wall construction in Bangladesh. The fibers used in different literature studies for earth block preparation had lengths between 10-40 mm and the percentage of fiber content ranged from 0% to 5% of the total dry weight [17], [18], [19]. For this study, 0.1 and 0.2% of the 15 mm long fiber of the total weight of soil was fixed based on a literature review. In the previous research we also found water added to earth block production ranges from 10 to 13% [20] and here, 12.5% water content was selected for the mix. Soil cement was mixed until a uniform mix of colors was obtained. Then the fiber was spread by three layers on the mix and again a uniform mix was ensured. This procedure was done in three layers to get the most uniform mix.

Sample Preparation

5 different categories of specimen groups were designed by adding different materials to the dry soil and presented in **Table II**. For each combination, 4 separate samples were prepared for achieving the average value. The metal molds were specially prepared for this study having an inner dimension of 100mmx100mmx100mm. The mold wall has a 2mm thickness joined with 12 bolts. After preparation, the mixture was poured into three layers, and manual compression was applied for each layer. Fig. 3, shows the mixture preparation, casting procedure, and prepared mud block. When the casting is complete, the mold was left in the air for 24 hours. Then the bolts were removed carefully using necessary tools and the prepared sample was carefully taken out from the mold. After that, the wet compressed earth block was placed in an open space for sun drying for 28 days.

Thermal properties measurement

The portable meter TLS-100 was used to measure the thermal conductivity and resistivity of the specimens according to ASTM D5334-14. A narrow heating wire and a temperature sensor are sealed in a steel tube of the sensor needle which is completely inserted into the sample to be tested. Heat is transferred to the specimen constantly and the temperature increase is recorded for a defined period. The calculation of thermal conductivity was done by using the slope from the plot of temperature increase versus the logarithm of time. The instrument and the measuring procedure is shown in **Fig. 4**.

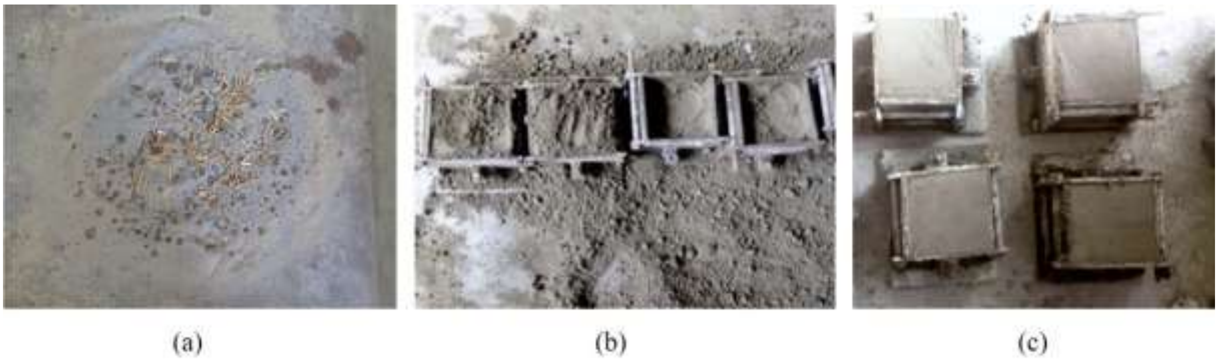


Fig. 3 (a) Uniform mix preparation (b) manual pressing of soil mix after pouring (c) prepared mud block with mold

(a) Instrument (b) Procedure

Fig. 4 Thermal Conductivity Coefficient Measurement Procedure

Table III Thermal Conductivity Coefficients and Density of Mud Blocks.

Sample No	***k* (W/mK)**	**ρ (kg/m^3)**
A	0.492	1840
B1	0.477	1960
B2	0.510	1980
B3	0.279	1920
B4	0.353	1930

3. Findings

The thermal conductivity coefficient of the four specimens under one mixture proportion was calculated to find the average. The value was not considered in calculating the average if the individual deviation was more than ±5% of the average. Table **III** presents the average thermal conductivity coefficient of all the samples. The result shows, the thermal conductivity coefficient decreases with the addition of fiber but increases with the addition of cement. The thermal conductivity of B1 is less than that of the traditional mud block, but for B2 with the addition of 5% more cement, it rises almost 7%.

The lowest conductivity coefficient was found in B3, whereas for B4, like the previous trend, it increased with the addition of cement. For 0.2% straw fiber, the blocks showed 28% to 42% lesser value indicating a lower rate of heat conductivity than the traditional mud block. As straw fiber is hollow in nature with big pores, the density is reduced with the increase in the percentage of fiber, and thermal conductivity is decreased. The higher porosity of straw fibers results in low thermal conductivity which indicates higher thermal insulation.

As B3 showed the lowest thermal conductivity which leads to less heat gain, we used the parameters of B3 for the thermal performance simulation and comparison to understand whether straw fiber reinforced earth block provides better thermal insulation than CGS sheet, fired clay brick, and concrete.

4. Thermal Performance Evaluation

To assess the environmental performance of straw-reinforced mud block specific thermal properties (heat capacity) were calculated according to the mixture proportion and were used as energy simulation models parameters. To assess the environmental performance of brick, concrete, CGS sheet, and SMB structures, AT, MRT, and OT were taken for each of these materials.

1) Material Properties and Construction

A single-story residential model was created using the building energy simulation tool Energy Plus considering SMB as the wall material and its thermal performance was measured. Three additional models made of conventional materials—brick, concrete, and CGS sheet were also built to compare the outcomes. This study extensively used the TMY data (hourly weather data and outside design parameters) produced by Energy Plus, Dhaka 419230 SWERA.

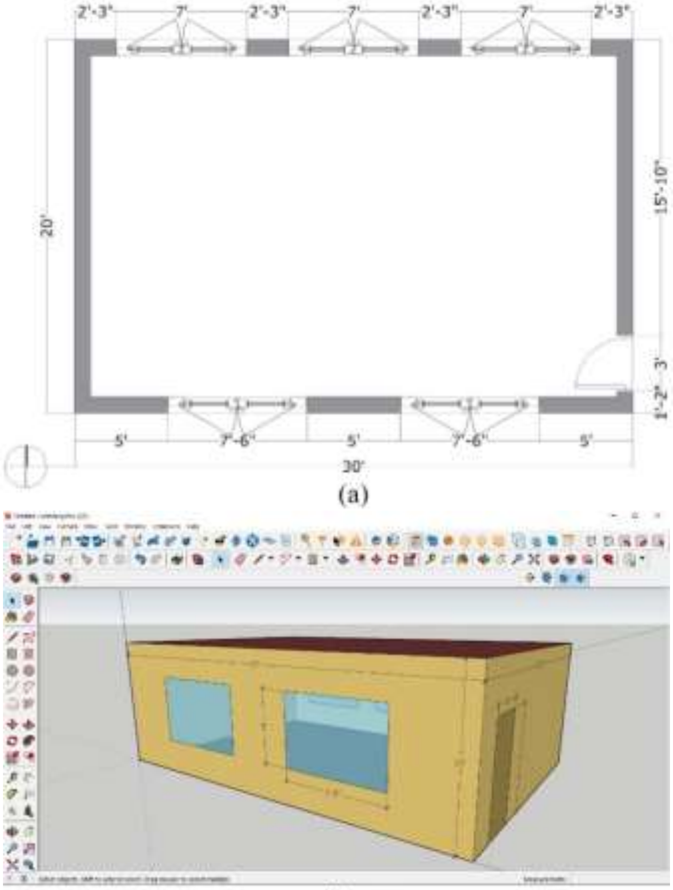
The model built for this study is a rectangular single-story structure with windows on the south and north sides. The building was a one-zone space with no internal divisions.

Fig. 5, and

Table IV provide a schematic of the structure and its measurements. The north-facing wall has three windows with a broad area of 105 m^2, resulting in a 35% WWR (window wall ratio), whereas the south-facing wall has two windows with the size shown in

Table IV, a broad area of 75 m2 resulting in a 25% WWR. According to research for the Asian standard for sustainable construction, a WWR of 25% was recommended for an opaque envelope, except for a lower 50% of the north face of envelopes in the climatic zone (1A: hot-humid zone) [21]. Further, there is a door on the east façade.

The models were altered to incorporate 254 mm (10 inches) thick walls except for 0.6mm for the CGS sheet, a 152 mm thick roof, and floor slabs with 6.35 mm exterior and internal plaster lining. The four distinct wall types were used in the simulation, and the material input data for thermal conductivity (*k*), specific heat (*Cp*), and density (ρ) were taken from **Table V**. To compare the values, the models only modified the inputs for the wall materials, leaving the wall thickness (except for CGS sheet), roof and floor design and construction the same. The thermal characteristics of all other materials except SMB were determined using data from literature study [22], [23] as shown in **Table V**.



(a)

(b)

Fig. 5 (a) Plan of the thermal model and (b) Front (southern facade) view of the schematic thermal model

Table IV Dimensions of the schematic models

	Width (m)	Height (m)	Length (m)
Building	6.096	3.048	9.144
Southern front window	2.286	1.524	-
Northern back window	2.134	1.524	-
Door (east)	0.914	2.134	-

Table V Thermal properties of the materials

Materials	*k* (W/m-K)	ρ (kg/m^3)	*Cp* (J/kg-K)
Brick	0.55-1.34	1200-1790	1172-1450
Concrete	1.95	2240	900
Plaster	0.43	2375	650-753
CGS sheet	50	7800	480
SMB	0.279	1920	1220.63

Table VI Schedule for window opening and closing

Timing		**Windows**	**Ventilation**
Summer (26-29) April	Days 07:00 – 22:00	Open	Cross ventilation
	Night 22:00 – 7:00	Open	Cross ventilation

The simulation model's default exposure settings, which include a sub-urban topography, complete interior and external solar distribution, total sun/wind exposure on walls and roofs, and no sun/wind exposure on the floor, were left intact for this project. Additionally, the HVAC settings were left alone. ASHRAE 189.1-2009 Res Ext Window for Climate Zone 1 (simple operable windows) was used for the simulation. In addition to using natural ventilation, all readings were obtained with the thermal zone's open windows and closed doors. The schedule for opening and shutting the simulation model windows is shown in **Table VI**. As a default setting for summer design days, Energy Plus's weather suggestions for Dhaka were utilized. The highest dry-bulb temperature on the summer design day was 30.90° C. The default ground temperature for each simulation was set to stay at 18° C.

5. Result And Discussion

The data was collected for the summer days from 26 April to 29 April. The zone AT, MRT, and OT for each hour of the summer design days were calculated for each simulation in Energy-Plus and are included in the output file. The min, max, mean, and standard deviation (SD) values were also determined to compare the thermal performance of the four varied materials. The results are displayed in **Table VII** for the summer design days.

Table VII Indoor air temperature (AT) comparison for different wall materials (summer days)

Statistic	Outdoor AT [°C]	Indoor AT [°C]			
		Brick	Concrete	CGS	Mud Block
Minimum	20.60	20.33	20.43	20.05	20.23
Mean	24.49	24.75	24.73	25.79	24.89
Maximum	30.90	32.99	32.59	37.90	30.97
SD	2.84	2.55	2.48	3.54	2.20

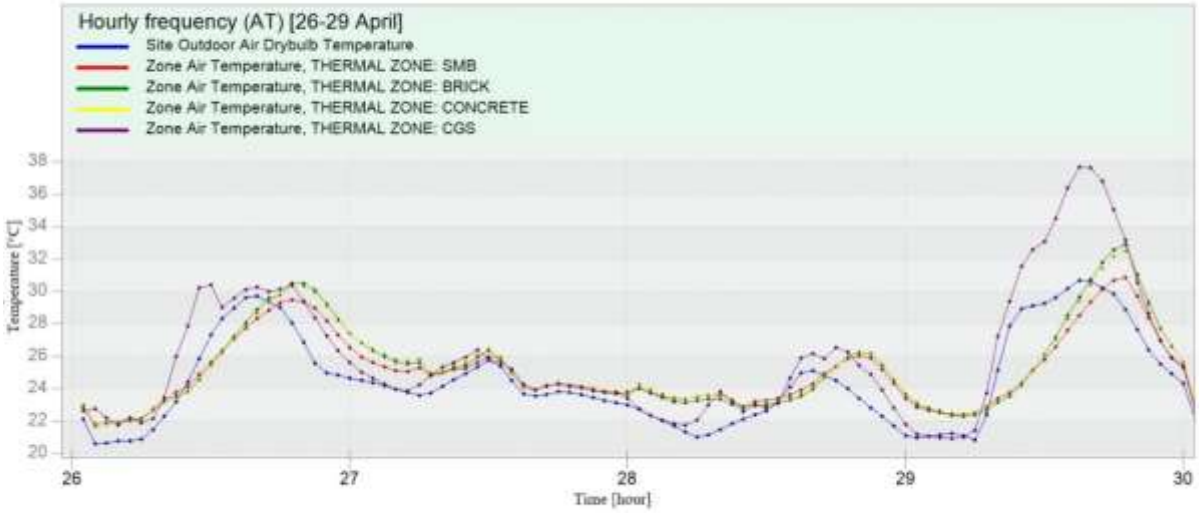


Fig. 6 Zone air temperature (summer days)

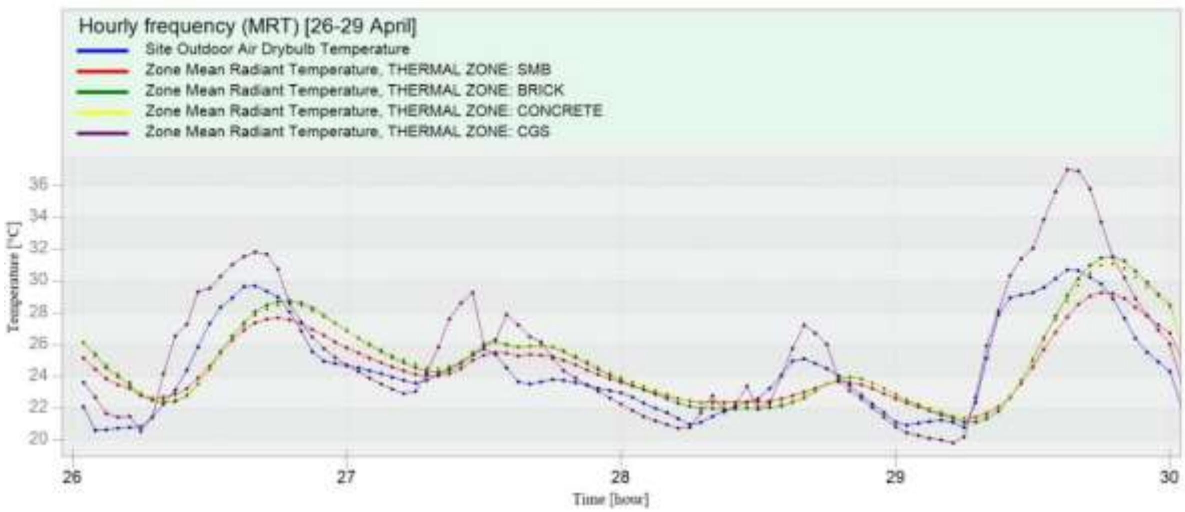


Fig. 7 Zone mean radiant temperature (summer days)

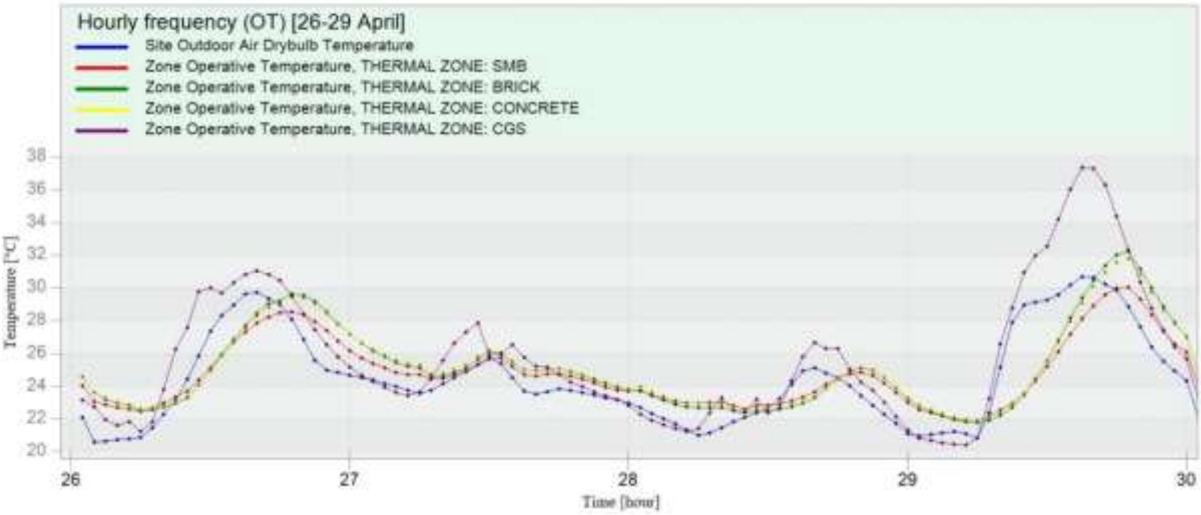


Fig. 8 Zone operative temperature (summer days)

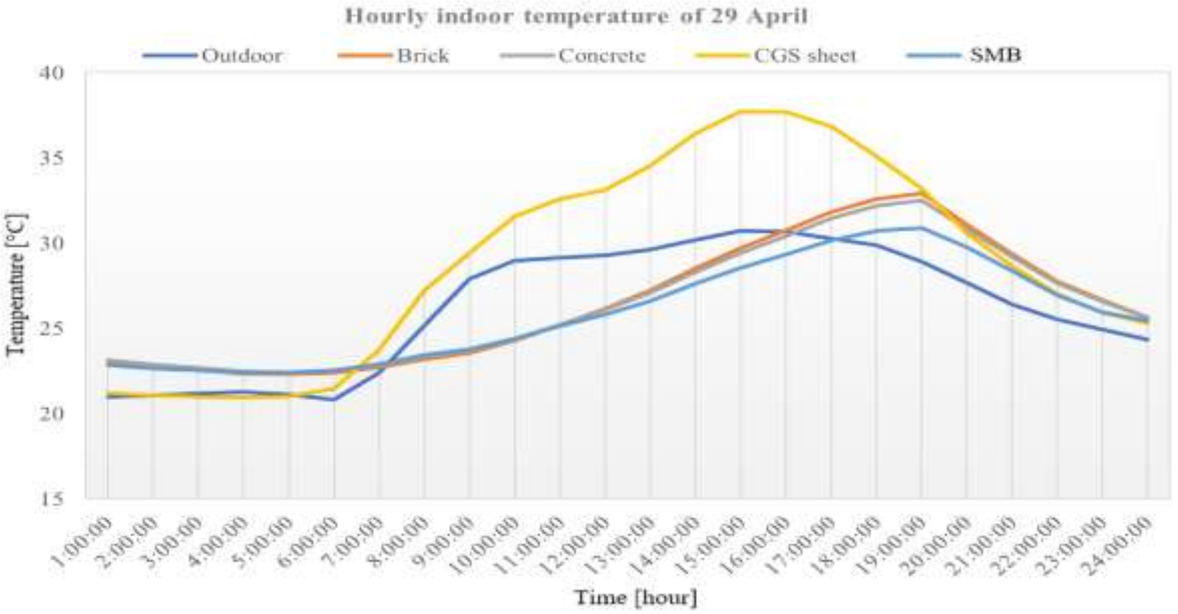


Fig. 9 29 April hourly Air temperature (AT) [C]

SUMMER DAYS PERFORMANCE

Fig. 6, **Fig. 7**, and **Fig. 8** present the thermal performance (AT, MRT, OT) of different building materials, including brick, concrete, CGS sheet, and SMB. The data was obtained from four days in April (26-29), and the outdoor temperature was also measured and included in the simulation. Overall, this analysis provides valuable insight into the thermal properties of different building materials and their impact on indoor temperature.

Based on the research findings, it seems that using mud blocks in the building envelope can significantly reduce the indoor temperature compared to conventional brick, concrete, and CGS sheet structures, which aligns with the findings of related research [24].

Additionally, incorporating straw into the mud blocks can provide even better thermal conditions. The simulations predict a decrease of 5-18% in indoor temperature and a 1-38% lower standard deviation, resulting in a better thermal indoor environment Table VII. It is important to note that there is a correlation between the thermal conductivity and the thermal performance of the materials, meaning that lower thermal conductivity results in a higher temperature difference between the outdoor and indoor zones, providing a better thermal environment.

Fig. 9, illustrates the simulated hourly indoor temperature of 29 April of four structurally identical buildings constructed from different materials in comparison to the outdoor temperature. At approximately 07:00, the indoor temperatures are in equilibrium with the outdoor temperature at around 23°C. Gradually both the outdoor and indoor temperatures increase until the outdoor peaks at approximately 31°C at 15:00, with the SMB building exhibiting the lowest peak at around 28°C. Conversely, the CGS structure experiences a slightly faster heating rate compared to the SMB, brick, and concrete buildings, reaching a peak of approximately 38°C. Subsequently, the indoor temperatures steadily rise until they reach evenness with the outdoor temperature at around 17:00, achieving a temperature of approximately 30°C for the SMB building. However, whereas the apex of the SMB structure shows the lowest temperature, reaching around 31°C at 19:00, the outdoor temperature is slightly lower than the indoor temperature. In the case of the CGS sheet building, its indoor temperature peaks are relatively high, approximately 6-7°C higher than the outdoor peaks because of its high thermal conductivity as indicated in **Table V**. Consequently, SMB demonstrates the best thermal performance, with the brick and concrete buildings falling in between. Regarding minimum temperatures, the internal minima are slightly 1-2°C higher than the outdoor minima due to night-time ventilation measures implemented to facilitate the cooling of the buildings.

Nonetheless, the simulation outcomes have been found encouraging for achieving a better indoor environment in the summer season. Using stabilized mud blocks can be a potential construction technic for better energy-efficient buildings. While the evaluation used a basic structure with simplifications, it still provided valuable insight into the thermal performance benefits of stabilized mud blocks in building envelopes.

6. Conclusion

Based on the research conducted, it has been confirmed that SMB blocks are an appropriate indoor environment-modifying building material that can ensure indoor thermal comfort. SMB block sample B3 presented the best thermal performance among all the tested samples lowering the Thermal conductivity coefficient by 43% than the non-stabilized mud block and simulated indoor temperatures using B3 as wall material during summer were in good agreement. The internal temperature peaks of the SMB model were the lowest during the summer period, 1-9°C lower than conventional materials, and they also indicated a lower variation of SD for indoor AT, MRT, and OT. Therefore, it can be concluded that SMB has modest potential as an alternative building material, and architects and engineers can develop low energy-intensive spaces in tropical climates using this approach.

References

[1] M. Madrid, A. Orbe, H. Carré, and Y. García, “Thermal performance of sawdust and lime-mud concrete masonry units,” *Constr. Build. Mater.*, vol. 169, pp. 113–123, Apr. 2018, doi: 10.1016/J.CONBUILDMAT.2018.02.193.

[2] F. Fiorito, “Phase-change materials for indoor comfort improvement in lightweight buildings. A parametric analysis for Australian climates,” *Energy Procedia*, vol. 57, no. 0, pp. 2014–2022, 2014, doi: 10.1016/j.egypro.2014.10.066.

[3] N. Soundarya, “Effect of fly ash and GGBS on lime stabilized mud block,” *Mater. Today Proc.*, vol. 47, pp. 4636–4640, Jan. 2021, doi: 10.1016/J.MATPR.2021.05.481.

[4] P. D. Onodagu, F. C. Uzodinma, and C. H. Aginam, “Effects of untreated oil-palm fruit fibre reinforcements on the strength and durability properties of non-fired pressed mud blocks,” *Niger. J. Technol.*, vol. 41, no. 1, pp. 1–6, 2022, doi: 10.4314/njt.v41i1.3.

[5] N. Uddin, “A study on the traditional housing technology of Bangladesh,” *Indian J. Tradit. Knowl.*, vol. 7, no. 3, pp. 494–500, 2008.

[6] S. Deboucha and R. Hashim, “A review on bricks and stabilized compressed earth blocks,” *Sci. Res. Essays*, vol. 6, no. 3, pp. 499–506, 2011, doi: 10.5897/SRE09.356.

[7] P. J. Walker, “Strength and Erosion Characteristics of Earth Blocks and Earth Block Masonry,” *J. Mater. Civ. Eng.*, vol. 16, no. 5, pp. 497–506, 2004, doi: 10.1061/(asce)0899-1561(2004)16:5(497).

[8] S. N. Malkanthi, W. G. S. Wickramasinghe, and A. A. D. A. J. Perera, “Use of construction waste to modify soil grading for compressed stabilized earth blocks (CSEB) production,” *Case Stud. Constr. Mater.*, vol. 15, p. e00717, Dec. 2021, doi: 10.1016/J.CSCM.2021.E00717.

[9] C. Jayasinghe and N. Kamaladasa, “Compressive strength characteristics of cement stabilized rammed earth walls,” *Constr. Build. Mater.*, vol. 21, no. 11, pp. 1971–1976, 2007, doi: 10.1016/j.conbuildmat.2006.05.049.

[10] S. Paul, M. S. Islam, and T. E. Elahi, “Comparative effectiveness of fibers in enhancing engineering properties of Earth as a building Material: A review,” *Constr. Build. Mater.*, vol. 332, p. 127366, May 2022, doi: 10.1016/J.CONBUILDMAT.2022.127366.

[11] M. Revuelta-Aramburu, A. Verdú-Vázquez, T. Gil-López, and C. Morales-Polo, “Environmental analysis of the use of plant fiber blocks in building construction,” *Sci. Total Environ.*, vol. 725, p. 138495, Jul. 2020, doi: 10.1016/J.SCITOTENV.2020.138495.

[12] V. Rigassi, *Compressed Earth Blocks : Manual of Production*, vol. I. 1985.

[13] R. Bahar, M. Benazzoug, and S. Kenai, “Performance of compacted cement-stabilised soil,” *Cem. Concr. Compos.*, vol. 26, no. 7, pp. 811–820, 2004, doi: 10.1016/j.cemconcomp.2004.01.003.

[14] G. Minke, “Construction manual for earthquake-resistant houses built of earth,” *Build. Advis. Serv. Inf. Netw.*, p. 52, 2001, [Online]. Available: http://cd3wd.com/cd3wd_40/GTZCRYS3/h4257e.pdf.

[15] M. Francisco and C. Granja, “Compressed earth blocks with and without cementitious materials,” pp. 1–13, 2012.

[16] A. B. Ngowi, “Improving the traditional earth construction: A case study of Botswana,” *Constr. Build. Mater.*, vol. 11, no. 1, pp. 1–7, 1997, doi: 10.1016/S0950-0618(97)00006-8.

[17] A. O. Dawood, F. I. Mussa, H. Al Khazraji, H. A. A. Ulsada, and M. M. Yasser, “Investigation of Compressive Strength of Straw Reinforced Unfired Clay Bricks for Sustainable Building Construction,” *Civ. Environ. Eng.*, vol. 17, no. 1, pp. 150–163, 2021, doi: 10.2478/cee-2021-0016.

[18] C. M. Chan, “Effect of natural fibres inclusion in clay bricks: Physico-mechanical properties,” *World Acad. Sci. Eng. Technol.*, vol. 73, no. 1, pp. 51–57, 2011.

[19] R. Illampas, V. G. Loizou, and I. Ioannou, “Effect of Straw Fiber Reinforcement on the Mechanical Properties of Adobe Bricks,” *Poromechanics 2017 - Proc. 6th Biot Conf. Poromechanics*, vol. 0609, no. April 2018, pp. 1331–1338, 2017, doi: 10.1061/9780784480779.165.

[20] H. Chaib, A. Kriker, and A. Mekhermeche, “Thermal Study of Earth Bricks Reinforced by Date palm Fibers,” *Energy Procedia*, vol. 74, pp. 919–925, 2015, doi: 10.1016/j.egypro.2015.07.827.

[21] J. W. Lee, H. J. Jung, J. Y. Park, J. B. Lee, and Y. Yoon, “Optimization of building window system in Asian regions by analyzing solar heat gain and daylighting elements,” *Renew. Energy*, vol. 50, pp. 522–531, 2013, doi: 10.1016/j.renene.2012.07.029.

[22] S. Chowdhury, K. S. Ahmed, and Y. Hamada, “Thermal Performance Evaluation of Cavity Air-Gap for Tropical Factory’s Envelope,” *Int. J. Archit. Eng. Constr.*, vol. 6, no. 4, pp. 1–12, 2017, doi: 10.7492/ijaec.2017.019.

[23] Y. Camara, D. Ouedraogo, L. G. Sawadogo, and A. Compaore, “Comparative Study of the Thermal Performance of three pitched Roof Models for a Humid Tropical Climate : case of Guinea,” vol. 13, no. 7, pp. 791–803, 2022.

[24] S. Shaik, K. K. Gorantla, and A. B. T. P. Setty, “Investigation of Building Walls Exposed to Periodic Heat Transfer Conditions for Green and Energy Efficient Building Construction,” *Procedia Technol.*, vol. 23, pp. 496–503, Jan. 2016, doi: 10.1016/J.PROTCY.2016.03.055.