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PRACTICE-ORIENTED PAPER

Thermal comfort analysis of fired-clay brick, cement-sand block and cement stabilized earth block masonry house models

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Abstract

Fired-clay brick, cement-sand block and cement stabilized earth blocks are the most commonly used material for masonry construction in Sri Lanka. Strength, durability and cost are three major factors that influence the selection of material for wall construction. Even though Sri Lanka has a tropical climate, the benefits of insulating the external walls of the house are often not considered. Apart from thermal comfort of the internal environment, there is concern regarding increase in energy consumption. However, in recent years, as awareness of sustainable and green building concepts increased, interest in using sustainable and thermal comfort materials for house construction has increased. Because external walls play a major role in thermal insulation, there is a need to select suitable wall materials that can be energy efficient and reduce cooling load. Therefore, the present study aims to understand thermal comfort in house units constructed with commonly used wall material such as fired brick, cement-sand block and cement stabilized earth block. Temperature and humidity inside and outside house models were observed to compare the impact of masonry materials on thermal comfort. To compare the thermal comfort performance of the house models, three thermal comfort analysis models: steady-state comfort model, adaptive criteria model and deterministic models were used according to the British Standard European Norm (BS EN) 16798, CIBSE TM52 and ANSI/ASHRAE 55. Results show that house units constructed with cement stabilized earth blocks and fired-clay bricks are significantly more comfortable in terms of temperature and humidity variations. Energy-efficient house units thereby minimized energy consumption through reduction in indoor temperature. Therefore the cement stabilized earth block and fired-clay brick house model are found to be a suitable choice for construction.

Keywords Masonry · Bricks · Cement-sand blocks · Cement stabilized earth block · Thermal comfort

Introduction

Nowadays, energy is one of the main aspects that play a vital role in socio-economic development in all countries. The energy consumption of building materials turns out to be an important factor in the determination of the energy efficiency of the construction. In the life-cycle of the construction in every phase, energy consumption happens at different levels. The selection of suitable building material increases energy efficiency of a construction [1].

Heating and cooling of common buildings consume a huge amount of energy. For several countries, the energy consumed to attain thermal comfort of the indoor is observed to be half the amount of energy generated. Applying thermal insulation to the wall or selecting energy-efficient wall materials are few techniques to reduce indoor air temperature naturally [2]. In addition, this can also reduce the cost of cooling of indoor space, energy consumption and as a result reduce pollution of the environment [3]. Engineers, architects, planners and other responsible people consider better ways to reduce energy usage in buildings and especially in residential house units. By use of proper materials for masonry walls in a building with proper techniques, the energy consumption of a building can be minimized [4]. Generally, the masonry unit type used for the construction predominantly influences the thermal condition inside the building.

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Problem statement

Masonry is the predominant construction material for house units in Sri Lanka, where more than 90% are constructed using materials such as cement-sand blocks, bricks, compressed earth blocks and mud (Fig. 1) [5]. Even though cement and bricks are most used for house construction in Sri Lanka, in recent years, due to their sustainability and lower cost, the use of cement stabilized earth blocks has become popular. Each wall material has its merits and disadvantages. While cement-sand blocks and bricks are strong and durable, the process of production of brick and cement-sand blocks is pollution-intensive and are relatively costly. In addition, the production of brick and cement-sand blocks require fine aggregates, which are obtained from river beds and agricultural lands, respectively. Over excavation of river sand and agricultural soil also damages the environment [6]. On the other hand, the production of cement stabilized earth blocks is comparably sustainable. However, when they are used in high-rainfall regions, the durability of the blocks remains challenging [7]. Therefore, to confront the challenges of infrastructure development, a more inclusive strategy must be adopted for better results [8].

On the other hand, Sri Lanka is located in a hot tropical zone. In the past years, during the building design or construction phase, the thermal comfort performance of the building is not considered. As a result, buildings show poor thermal comfort performance and artificial cooling systems are therefore used to achieve required thermal comfort. Air conditioners were used by locals to regulate the indoor temperature and humidity. Because of that, the electrical power consumption for cooling increased dramatically. Generally, power consumption of air conditioners is extremely high and it consumed around 60% of the total energy consumed by the building [9]. However, In recent years, Sri Lanka experienced several power outages as energy production reached its production capacity [10]. Therefore, the government demands people to limit consumption of power and focus on energy-efficient practices, including constructions. The most important heat gain in building comes from solar radiation through roof, external wall and openings [11]. To overcome this, researchers focus on low thermal conductivity building materials for wall construction.

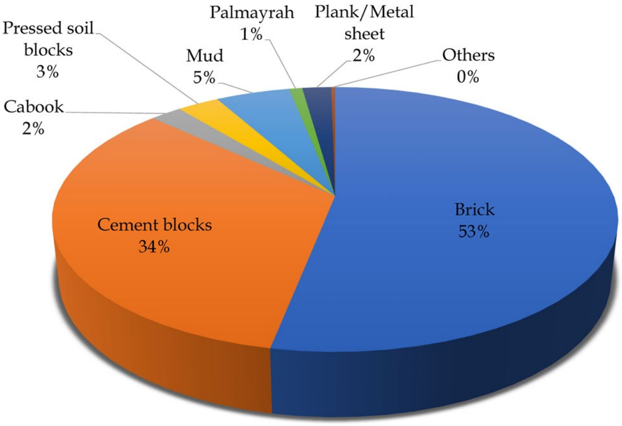


Fig. 1 The material used for house units in Sri Lanka [5]

Until recent times in Sri Lanka, the selection of wall material for house units depended on strength, durability and cost, while less importance was given to sustainability and thermal comfort. However, recent demand for energy consumption reduction, sustainability and green building concept has become the common interest of construction industries and especially for example, in finding sustainable material to provide increased thermal comfort of the indoor space. Contemporary literature has extensively covered analyses on their strength and durability characteristics [7, 12–23]. However, the investigation on thermal comfort of such materials used for masonry structure is scarce in the literature. Especially, identifying locally available suitable building material for masonry wall construction, which can reduce the energy consumption of the housing unit, requires extensive study.

Past studies

Several studies focused on developing energy-efficient construction materials incorporating agricultural waste materials. Energy consumption and carbon dioxide emissions can be reduced by incorporating renewable sources of energy, improving technologies and promoting eco-friendly alternative materials. For construction, substituting renewable material such as straw [19], kenaf fibers [18], jute [17], flax [16], coconut fiber [20, 21], hemp [13–15] cork [12], steel fibre [24] and pharmaceutical industrial wastewater [25], were proven to have lower environmental impacts compared with conventional construction materials. However, these studies focused on mechanical and durability characteristics of individual block units instead of overall thermal comfort performance of house units constructed with these blocks.

Few studies analyzed thermal comfort in house units constructed with different masonry units such as rice husk ash (RHA) based cement-sand blocks [26], fly ash bricks [27, 28], recycled paper mill waste cement bricks [27], bagasse ash bricks [28], cement mortar incorporating super absorbent polymer [29] and coconut fiber insulated hollow cement blocks [3]. In addition, Zafra et al. [30] conducted a study on thermal performance assessment of shipping containers as post-disaster housing in the tropical climate. Although these studies focused on the thermal comfort of house units constructed with particular materials and comparison to conventional material was not discussed.

Fasogbon et al. [31] investigated thermal comfort of the house model constructed with mud-brick, concrete blocks and cast concrete in Nigeria. The results established that even though fluctuations were observed in the outdoor air temperature, the indoor air temperature remained stable for both models made of mud-brick and cast concrete. Similar behavior was also observed in indoor humidity. Yet, a house model constructed with concrete blocks showed higher indoor temperature and humidity fluctuations. Moreover, high-level humidity was observed inside the concrete block house model, followed by the mud-brick house model, while in the cast concrete house model they were the least. However, this study only considered a single-day data and comparison done by simple overheating criteria (indoor air temperature compared with outdoor air temperature).

Udawattha and Halwatura [32] studied the thermal performance of houses constructed with brick, hollow cement block and mud concrete block where time lag and decrement factors were considered for comparison of thermal comfort. The study concluded that brick is the most thermally favorable building material, which has a longer time lag and low decrement factor. It is followed by mud concrete block and a hollow concrete block having the lowest time lag and highest decrement factor. The generalization of this study, however, is limited as it was based only on one-day observations from field measurements and simulation using computer software.

In addition, the authors studied commonly used masonry units for construction in Sri Lanka. The past studies mainly focus on the strength and durability characteristics of stabilized earth blocks, which become popular in Sri Lanka for house units' construction in recent years [7, 33–35]. Also, the authors reported the addition of natural fiber to cement-sand blocks and stabilized earth blocks, improves strength as well as durability [20, 21]. Further, several other studies considered sustainable development of cement-sand blocks and stabilized earth blocks with rice husk ash as cement replacement and agricultural waste as sand replacement [6, 36–38]. However, all these studies have limited to strength and durability of masonry blocks, while none focused on thermal comfortability analysis of house units constructed with these masonry units.

Research gap

Although several studies were conducted on energy-efficient construction material for masonry, most of the studies focused on mechanical and durability characteristics of individual blocks [12–21] and only selected studies focused on thermal comfort performance analysis. Among those studies, only Udawattha and Halwatura [32] and Fasogbon et al. [31] reported thermal comfort performance of house units constructed with conventional masonry units. All other studies were conducted in house units with agricultural or industrial waste incorporated cement blocks [3, 26–29], which are not commonly used in Sri Lanka. For both studies by Udawattha and Halwatura [32] and Fasogbon et al. [31], the studies were limited to single-day observations and analyses as well as only simple overheating as a critical parameter (indoor air temperature less than optimum temperature for acceptable comfort limit). Also, humidity data were not considered in any of these analyses.

With the issues mentioned above, the present study is the first attempt in Sri Lanka to quantify the thermal comfort level in small-scale house units constructed with commonly used masonry wall materials: fired-clay brick, cement-sand block and cement stabilized earth blocks.

Objective of the study

The present study considers the small-scaled house models, which were built with different masonry units in the same location where both temperature and humidity variations have been considered. The aim of the present study is to understand the thermal comfort of house units constructed with brick, cement-sand block and cement stabilized earth block. To compare their thermal comfort, temperature and humidity data were taken inside and outside the house models continually. The objectives of the study were,

- Compare indoor temperature and humidity of house models constructed with different masonry unit types and how the masonry unit type affects the time lag and decrement factor.
- Evaluate each house unit's thermal comfort performance on adaptive criteria according to the British Standard European Norm (BS EN) 16798 [39], CIBSE TM52 [40] and ANSI/ASHRAE 55 [41].
- Evaluate each house unit's thermal comfort performance on deterministic models according to the ANSI/ASHRAE 55 [41].
- Recommend the suitable building material for masonry wall construction in the hot tropical zone.

Methodology

Wall materials used

House models constructed with three material types such as fired-clay brick, cement-sand blocks (CSB) and cement stabilized earth blocks (CSEB) were used, as shown in Fig. 2, which are generally used in Sri Lanka. Since the main aim of the research was to investigate the thermal comfort of houses constructed with conventional masonry unit in Sri Lanka; it was thought the


(a) (b) (c)

Fig. 2 Type of masonry blocks used for house model construction **a** fired-clay brick, **b** CSB and **c** CSEB

same mixed proportion used in the sites was suitable and adequate for meeting the aims of the research. Therefore, CSB and CSEB blocks were cast with 1:6 ratio of cement to sand and cement to local soil, measured by volume, respectively.

To analyze the properties of these blocks, tests were conducted for water absorption rate, compressive strength, splitting tensile strength and flexural strength according to ASTM C140 [42], ASTM C109 [43], ASTM C1006 [44] and ASTM C1609 [45], respectively. Table 1 summarizes the mechanical characteristics of masonry units used in this experimental program. Brick showed better compressive strength in both wet and dry conditions than CSEB and CSB while it has shown lessor values for flexural and splitting tensile strengths. CSEB and CSB show higher compressive strength reduction due to wet conditions. In wet conditions, the hardened cement paste volume increased, and therefore the average distance between surfaces in the cement gel had increased, which in turn lowered the compressive strength of mortar [46]. Also, in CSEB, expansion of clay content in wet conditions further reduced the strength. When compared to brick and CSEB, CSB showed higher density and coefficient of thermal conductivity and lower specific heat capacity.

Description of design of house models and data collection

Three house models with a dimension of 1020 mm × 1020 mm × 660 mm were built. Model 1 was constructed of fired-clay bricks, model 2 was constructed of cement stabilized earth blocks and model 3 of cement-sand blocks. For each house model, a timber plate attached with 15 mm styrofoam on both sides, was used as a roof. 50 mm thick cement-sand mortar was used as the foundation for all three house models. The models are as shown in Fig. 3a and b. Temperature and humidity measurements were taken with the help of Arduino and DHT11 sensor as shown in Fig. 3c. Three temperature sensors (at top, middle and bottom parts of the house model) and one humidity sensor (at the middle of the house model) were placed inside and outside the house models.

Site description

House models were constructed in the university premises, Kilinochchi, Sri Lanka, which is located in the northern part of the country. Major construction materials used for house units in this area are cement blocks (49.6%),

Table 1 Properties of the masonry blocks and mortar

Properties	Brick	CSEB	CSB
Density (kg·m^{-3})	1677 ± 13	2050 ± 13	2084 ± 17
Water absorption (%)	18.6 ± 0.3	15.8 ± 0.2	13.0 ± 0.4
Porosity (%)	30.4 ± 0.2	31.7 ± 0.4	27.6 ± 0.8
Dry compressive strength (MPa)	6.57 ± 0.22	4.10 ± 0.19	3.94 ± 0.21
Wet compressive strength (MPa)	5.62 ± 0.19	2.23 ± 0.16	2.79 ± 0.22
Flexural strength (MPa)	0.47 ± 0.07	1.41 ± 0.07	1.55 ± 0.04
Splitting tensile strength (MPa)	0.44 ± 0.03	0.65 ± 0.09	0.89 ± 0.08
Thermal conductivity (W m^{-1} K^{-1})	0.506 ± 0.010	0.503 ± 0.013	0.581 ± 0.017
Specific heat capacity (kJ kg^{-1} K^{-1})	1.169 ± 0.021	1.532 ± 0.031	0.069 ± 0.019

(a) (b) (c)

Fig. 3 **a** House models, **b** house model with roof and **c** REDNO and temp sensor used for measurement

palmyras (20.8%), mud (14.2%) and metal sheet (8.4%) [5]. Even though this area is hot and humid throughout the year and brick is the major construction material used for house units in Sri Lanka, it is limited to 0.8% in this area. Figure 4 summarizes the monthly temperature and rainfall variation in Kilinochchi and it is shown that the area experiences a hot climate from March to October and temperature peaks in April. The rain period starts from October end and continues until the early part of January. For the present study, the period is selected from mid of December to mid of March. Generally, this season is a transient period, where the average outdoor temperature increased from 24 to 36 °C.

Thermal comfort evaluation

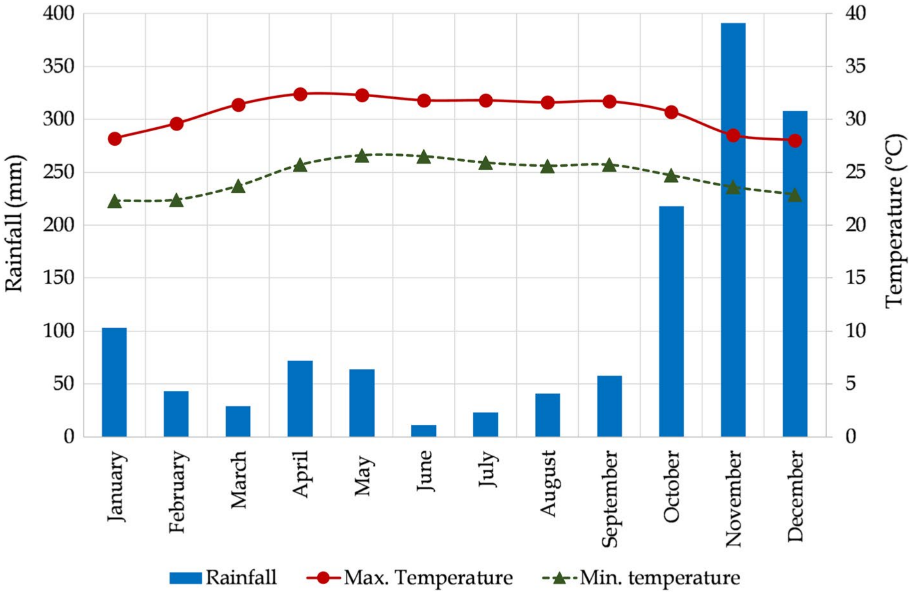
ANSI/ASHRAE 55 [41] defines thermal comfort as "the condition of mind that expresses satisfaction with the thermal environment". Most published guidance on the thermal comfort model can be divided into three categories.

- Steady-state comfort model
- Adaptive models
- Deterministic models

Steady-state thermal comfort model

Steady-state comfort is defined by acceptable temperature ranges, the condition when most individuals inside the building feel comfortable. CIBSE Guide A [47] specifies

Fig. 4 Weather history of the site (Kilinochchi, Sri Lanka)



the comfort temperature in naturally ventilated living rooms as 28 °C. For bedrooms, the maximum threshold is 26 °C. BS EN 16798 [39] suggests a comfortable temperature range of 20–27 °C for summer and 18–25 °C for winter. There are several national codes and researchers recommended different comfortable temperature ranges based on local conditions and field studies. For example, according to the Bureau of Indian Standard [48], 18 °C to 27 °C is considered the comfortable temperature range. On other hand, researchers recommended comfortable temperature based on a field study for different regions such as Malaysia [49], India [50–52], Qatar [53], Mexico [54], Japan [55], Brazil [56], etc. Depending on local climate conditions, these researchers recommended the comfort temperature in the range of 19 °C to 32 °C.

Humidity is another factor that affects thermal comfort. ASHRAE 55 [41] standard recommends relative humidity between 30 and 60% for thermal comfort. Chinese standard GB 18883 [57] recommends relative humidity of 40–80% in summer. For hot and humid conditions, several researchers also recommend this range (relative humidity between 40 and 80%) [58–61].

In hot and humid regions like Sri Lanka, it is rare to have an indoor temperature of less than 28 °C. For the present study, the neutral/comfort temperature range was considered as 19–28 °C. Also, the temperature of the indoor air within the 90% comfort limits (± 2.5 °C) and 80% comfort limits (± 3.5 °C) were considered. Several other researchers also followed similar approach [28, 62].

Adaptive thermal comfort model

In adaptive thermal comfort, models refer to an individual's thermal satisfaction that is determined by the individuals' experience of mean outdoor air temperatures.

The British Standard European Norm (BS EN) 16798 [39] recommends optimal temperature for comfort (T_{comf}) as a function of mean outdoor temperature (T_{o}) as shown in Eq. (1).

$$T_{\mathrm{comf}} = 0.33\,T_{\mathrm{o}} + 18.8 \tag{1}$$

However, they introduce three categories of expectation concept of acceptable indoor comfort temperature as high level of expectation only used for spaces occupied by very sensitive and fragile persons (Cat I), the normal level of expectation (Cat II) and a moderate level of expectation (Cat III). These categories of indoor comfort temperature are defined by plus or minus from optimal temperature for comfort recommended in Eq. (1). For Cat I, Cat II and Cat III thermal comfort, the upper limit is set as + 2 °C, + 3 °C and + 4 °C from optimal temperature, and the lower limit is set as − 3 °C, − 4 °C and − 5 °C from optimal temperature, respectively. Figure 5 shows the acceptable indoor temperature ranges for these categories. This comfort model is to be applicable to occupant-controlled naturally conditioned spaces, where the prevailing mean outdoor temperature falls between 10 and 30 °C [39].

CIBSE TM52 [40] recommends the maximum and minimum acceptable temperature for buildings in the free-running mode by Eqs. (2–3). This comfort model could be

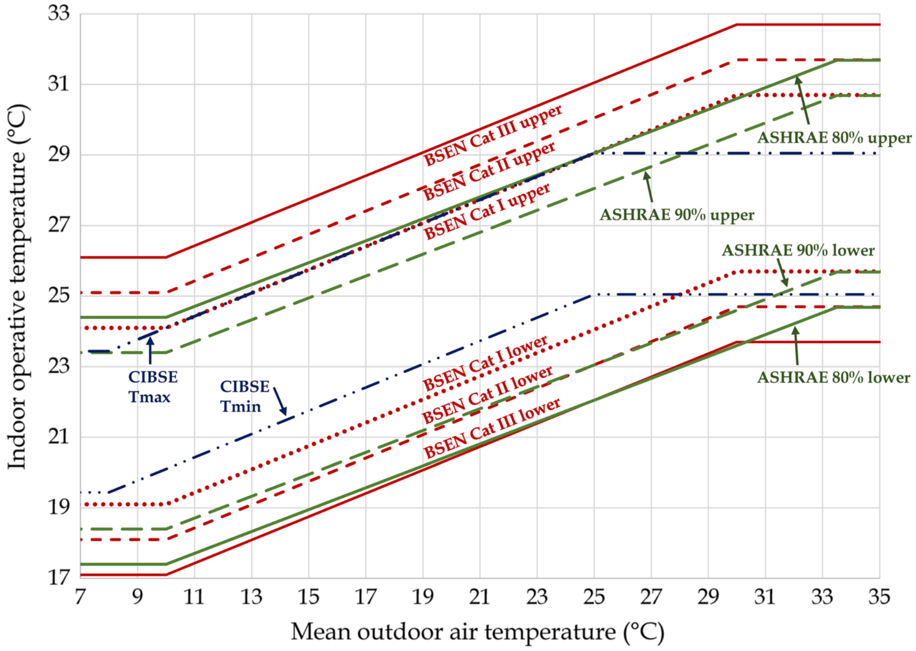


Fig. 5 Adaptive comfort models—BS EN 16798, CIBSE TM52 and ASHRAE 55

applied for the spaces where the prevailing mean outdoor temperature falls between 8 and 25 °C.

$$T_{\max} = 0.33\,T_{\mathrm{rm}} + 21.8 \tag{2}$$

$$T_{\min} = 0.33\,T_{\mathrm{rm}} + 15.8 \tag{3}$$

where $T_{\max}$ is the maximum acceptable temperature, $T_{\min}$ is the minimum acceptable temperature and T_{rm} is the running mean of the outdoor temperature.

The acceptable temperature range recommended by ASHRAE standard 55 is presented in Fig. 5. This standard defines the comfort zones within which 80% or 90% of individuals inside the building would feel the conditions acceptable. The comfort zones are defined by Eqs. (4–5). According to the ASHRAE, these equations can be used for naturally conditioned buildings. This comfort model could be applied for spaces where the prevailing mean outdoor temperature falls between 10 and 33.5 °C [41].

$$T_{\mathrm{comf}} = 0.31\,T_{\mathrm{o}} + 17.8 \tag{4}$$

$$T_{\mathrm{accept}} = 0.31\,T_{\mathrm{o}} + 17.8 \pm T_{\mathrm{limit}} \tag{5}$$

where T_{comf} is the optimal temperature for comfort, T_{accept} is the limits of the acceptable zones, T_{o} is the mean outdoor temperature and T_{limit} is the range of acceptable temperatures; for 90% = 2.5 °C and 80% = 3.5 °C.

Deterministic thermal comfort model

Deterministic thermal comfort models represent the thermal comfort for specific combinations of air temperature, relative humidity, airspeed and basal metabolic rate and clothing insulation [63]. The most recognized form of deterministic thermal comfort models is the Predicted Mean Vote (PMV), developed by Fanger [64]. PMV is scaled to predict thermal sensation votes on a seven-point scale (−3: cold, −2: cool, −1: slightly cool, 0: neutral, +1: slightly warm, +2: warm, +3: hot). In this scale, negative values indicate an uncomfortable feeling due to cold, positive values indicate an uncomfortable feeling due to a hot and zero indicates the comfort state. A similar point scale was adapted by the ASHRAE model too.

Results and discussion

Comparison of indoor and outdoor temperatures of model houses

Figure 6 shows the maximum and minimum temperature variation of indoor and outdoor air during the three months starting from December 15, 2019. It was observed that the average maximum temperature during this period for the brick house and CSEB house model was 4% and 5% cooler than the CSB house model, respectively. The maximum temperature in brick, CSEB and CSB house models were 5.3 °C, 5.7 °C and 3.9 °C lower than that of the ambient temperature, respectively. When considering minimum temperature, these values were 4.0 °C, 3.8 °C and 4.1 °C higher than that of the ambient temperature, respectively. This shows that the house model with CSEB and fired-clay brick can significantly reduce conduction heat gain in the house as a result of the decrease of room air temperature. On the other hand, CSB transfers outdoor heat through the wall and as a result, the indoor air temperature increased.

Thermal comfort based on simple overheating criteria

Indoor air temperature

Figure 7 presents the indoor air temperature variation of the brick, CSEB and CSB house models on a warm day (March 12, 2020). The average indoor air temperature was 32.3 °C, 30.3 °C and 32.4 °C for brick, CSEB and CSB house models, respectively. Simultaneously, the average temperature of the outdoor air was 30.2 °C. The temperature fluctuation was almost closer in both the brick (9.9 °C) and CSEB (9.0 °C) house models. However, temperature fluctuation for the CSB block house model was higher than the other two models and it was recorded as 11.5 °C. The maximum outdoor temperature observed during the daytime was 45.4 °C. The corresponding indoor air value was 37.9 °C, 35.3 °C and 39.3 °C for the brick, CSEB and CSB house model, respectively. Unlike CSB, fired-clay brick and CSEB have much better thermal mass. Because of the clay particles used to manufacture fired-clay brick and CSEB, they act as thermal mass. Therefore, they store and block heat flow through them. To analyze the comfort level on a particular day, the comfortable temperature was considered as 28 °C as per ASHRAE recommendation. The indoor air temperature of both brick and CSB house models showed that around 99.6% and 94.9% of the experimental days were under discomfort level, respectively. However, for the CSEB house model, it was reduced to 68.4% of the duration.

Figure 8 presents the indoor air temperature variation of the brick, CSEB and CSB house models on a cold day (January 4, 2020). The average indoor air temperature was 24.5 °C, 24.4 °C and 25.4 °C for brick, CSEB and CSB house models, respectively. The temperature fluctuation was almost closer in both the CSEB (8.0 °C) and CSB (8.1 °C) house models. However, the temperature fluctuation for the brick house model was significantly lower than the other two models and it was recorded as 6.6 °C. The average outdoor

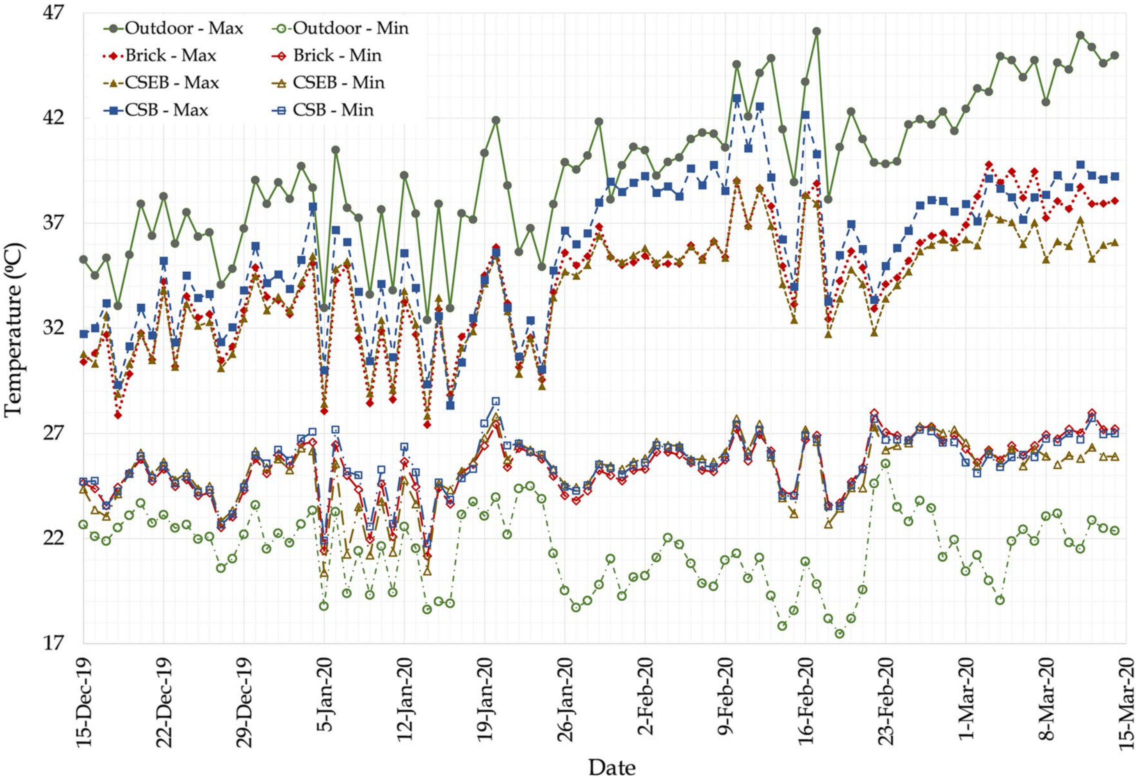
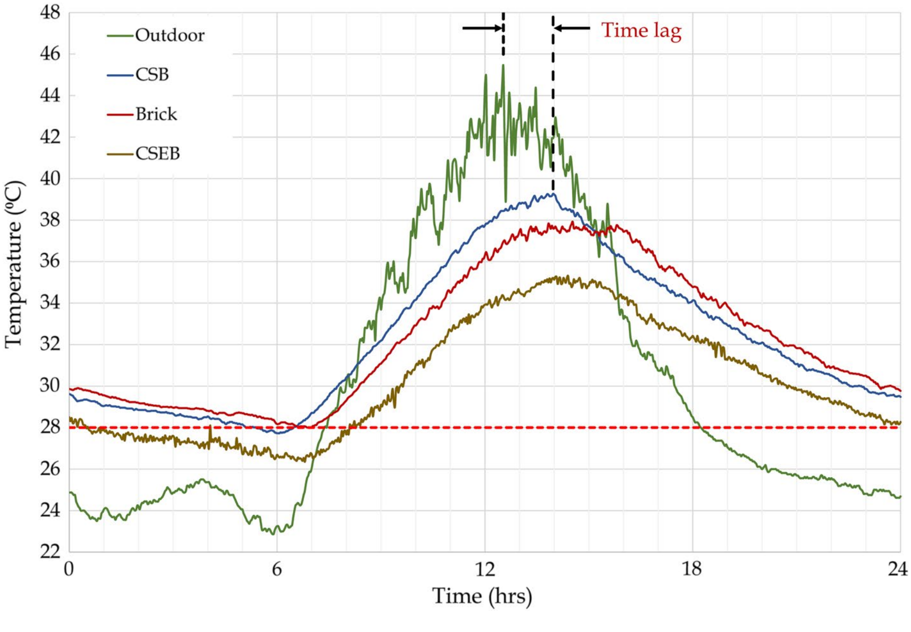


Fig. 6 Maximum and minimum temperature variation from 15th December 2019 to 15th March 2020

Fig. 7 Temperature variation during on a warm day (12th March 2020)



air temperature was 23.7 °C. When comfort temperature was set at 28 °C, both brick and CSEB house models had shown most of the days at a comfortable level. Brick and CSEB house models showed that 95.4% and 99.4% of the time, the indoor air temperature was less than 28 °C. But for the CSB house model, it reduced to 77%.

Table 2 provides the summary of the study on comparison of air temperature and humidity of the inside of house models during the study period (December 15, 2019 to March 15, 2020). The CSB house model was significantly warmer than the observation on the other two types of house models. Only 32.7% of the recorded hours were within the limit of

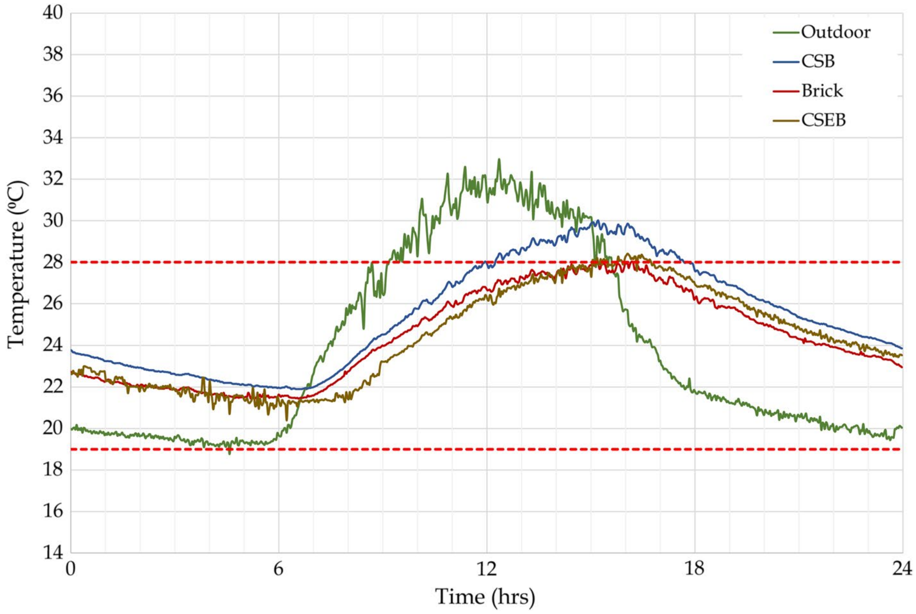


Fig. 8 Temperature variation during on a cold day (4th January 2020)

Table 2 Comparison of internal air temperatures and humidity measured inside house models (percentage of hours recorded from 15th December 2019 to 15th March 2020)

	Brick	CSEB	CSB
Temperature			
19.0–28.0 °C	34.9	35.5	32.7
28.0–30.5 °C	24.9	25.6	24.0
30.5–31.5 °C	7.9	8.9	7.3
> 31.5 °C	32.3	30.1	36.0
Humidity			
More than 80%	41.0	52.5	57.3
Between 40 and 80%	59.0	47.5	42.7
Less than 40%	–	–	–
Decrement factor			
More than 60%	2.2	5.6	31.1
Between 40 and 60%	91.1	87.8	62.2
Less than 40%	6.7	8.9	8.9

28^0C for the CSB house model. This was 2.2% and 2.8% lower than brick and CSEB house models, respectively. When 31.5 °C is considered as the upper threshold of acceptable temperature, 67.7%, 69.9% and 64.0% of the recorded hours were within the acceptable threshold for temperature.

Time lag

The time delay due to the thermal mass transfer is known as a time lag. On a warm day (March 12, 2020), the time lag was measured as 2 h. 00 min, 1 h. 52 min and 1 h. 25 min for brick, CSEB and CSB house models, respectively. This implies that the flux of heat takes more time to get through the fired-clay brick and CSEB than the CSB. In addition, it explains the time lag observed on the peak temperature due to the slow process of heating of the fired-clay brick and CSEB. On the other hand, CSB had less resistance to a thermal mass transfer on a warm day. Materials with low thermal conductivity, high specific heat capacity and high density will tend to have a longer time lag. Even though CSB had higher density, lower specific heat capacity than both brick and CSEB led to a shorter time lag. In contrast, the high density and high specific heat capacity of CSEB contributed to its extended time lag. On a cold day (January 4, 2020), the time lag was measured as 2 h. 57 min, 3 h. 42 min and 2 h. 51 min for brick, CSEB and CSB house models, respectively. It was shown that, when the outside temperature was less than the indoor temperature, CSEB was more resistant to the thermal mass transfer.

Decrement factor

The decrement factor is defined as the reduction in cyclical temperature on the inside air compared to the outside air [65]. The decrement factor represents structural cooling ability of building materials [32]. The lower value of decrement indicates that the heat transfer is effectively controlled by wall material. Decrement factor measured during the particular warm day was 0.44, 0.40 and 0.51 for brick, CSEB and CSB house models, respectively. The results show that porosity and specific heat capacity of the building materials have direct positive correlation with decrement factor. As was expected, a lower decrement factor that reduced summer overheating, in turn, lead to better performance of CSEB on a hot day. Therefore, CSEB performs better in terms of thermal comfort, compared to other housing materials. On a cold day, the decrement factor was 0.47, 0.56 and 0.57 for brick, CSEB and CSB house models, respectively. As expected, a higher decrement factor on a cold day indicated better performance of CSEB and CSB on a cold day.

Throughout the period, it was observed that the decrement factor was more than 60% for one-third of the recorded hours in CSB house models. However, for brick and CSEB house models, the decrement factor was between 40 and 60% for most of the period. In all three house models, the decrement factor rarely decreased lower than 40%. In the overall analysis, when the temperature was the only parameter considered for thermal comfort as a criterion, both brick and CSEB house models showed better thermal comfort performance than CSB house models.

Indoor air humidity

Figure 9 presents the indoor relative humidity variation for brick, CSEB and CSB house models on a warm day. The relative humidity inside the house models varied between 48 and 72% for all models. The general trend showed that nighttime indoor air humidity was significantly less than outdoor air humidity and the contrast during the daytime. The minimum internal relative humidity values for brick, CSEB and CSB house models were 48.1, 52.6 and 50.2%, respectively. Also, the brick house model had the lowest maximum relative humidity among the three house models while all three house models were within the acceptable upper level of 80%.

Figure 10 presents the indoor relative humidity variation for brick, CSEB and CSB house models on a cold day. The relative indoor humidity remained high at more than 75% for all house models. Brick and CSB house models had a humidity observation within the acceptable level of 80% from 3.18 to 6.08 pm and 2.28 to 6.06 pm, respectively. Except for this period, both brick and CSB house models experienced relative humidity reaching higher than 80%. On the other hand, the CSEB house model experienced relative humidity above 80% all through the 24 h.

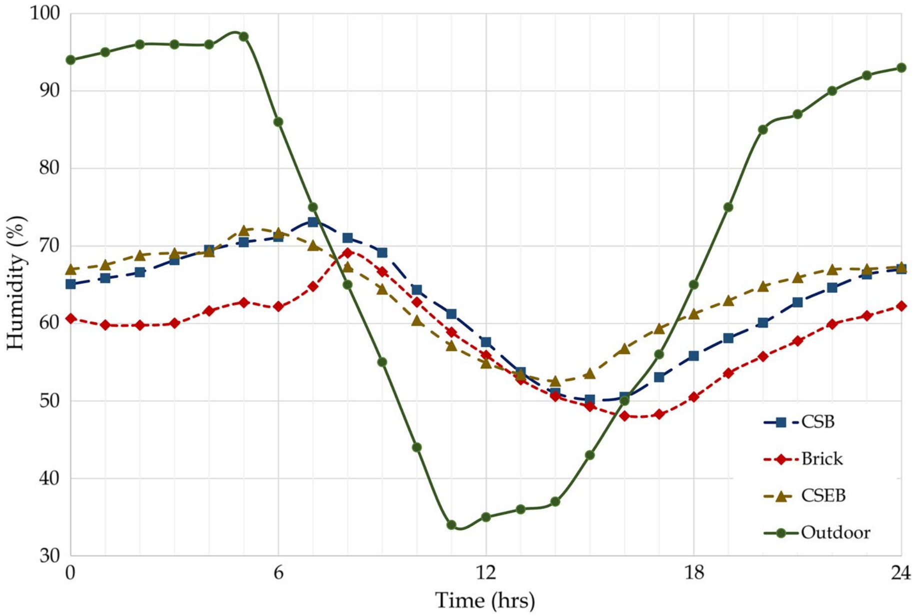
Throughout the period, the humidity was more than 40% for all three house models (Table 2). When the comfortable humidity range was considered as 40% to 80%, the brick house model showed 59% of the recorded hours within the comfortable threshold, where the same was 11.5% and 16.3% higher than CSEB and CSB house models.

Thermal comfort based on adaptive criteria

Figure 11 summarizes the daily indoor air temperature and the corresponding mean daily outdoor temperature. Graph produced points for each day and these have been divided into daytime and nighttime. It was evident that in all house models, indoor air temperatures correlatively rise with outdoor temperature. It was also noted that nighttime temperatures were usually within the BS EN Cat II threshold. However, in the daytime, there were several occurrences when temperatures were above the Cat III upper threshold. Especially, this is observed frequently for the CSB house model compared with the other two house models.

The measured temperatures in all three house models were compared using the bar chart approach recommended in BS EN 16798 (Fig. 12) and ASHRAE (Fig. 13). It was shown that the CSEB house model performed better in thermal comfort compared with other house models with 64.3% of the recorded hours under Cat I comfort zone as per BS EN 16798. The corresponding value for brick and CSB house models were 62.6% and 52.8%, respectively.

Fig. 9 Humidity variation during a warm day (12th March 2020)



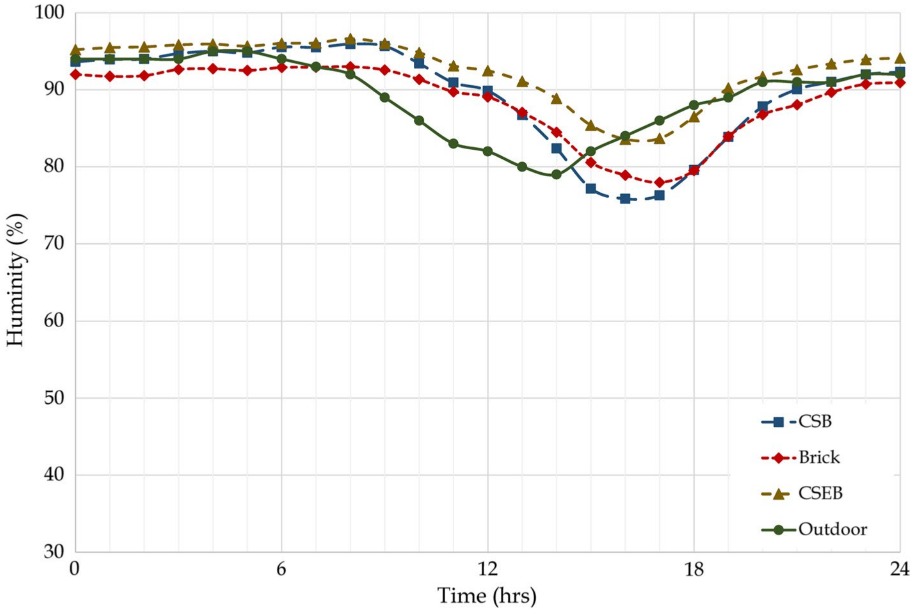


Fig. 10 Humidity variation during a cold day (4th January 2020)

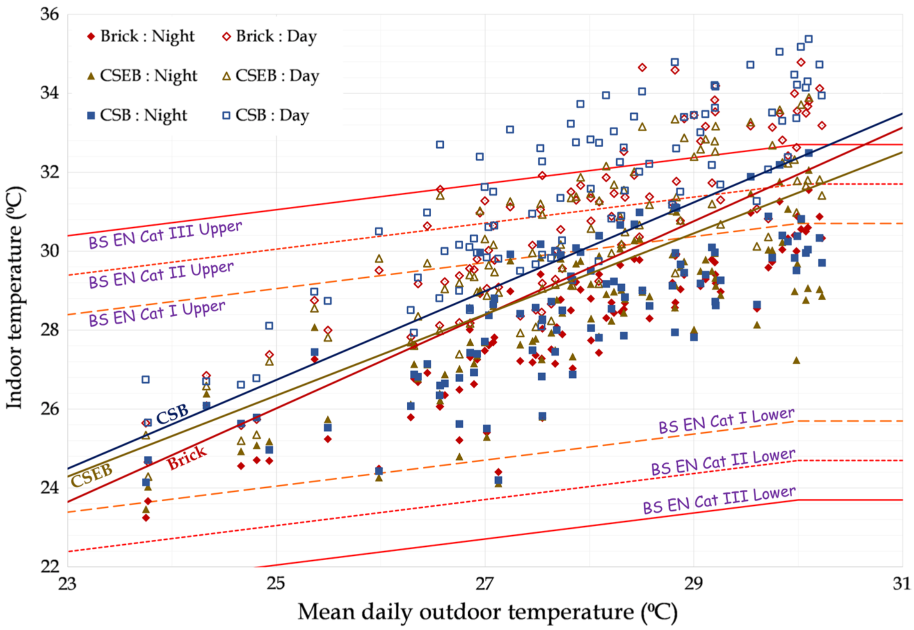


Fig. 11 Internal temperatures of the house models compared to BSEN16798 category limits

When Cat II comfort zone was considered as the acceptable limit, these values increased to 76.4%, 79.7% and 69.2% for the period for brick, CSEB and CSB house models, respectively.

When ASHRAE standard was adopted, similar thermal comfort was observed as 42.8% of the period was between 90% comfort zone threshold for brick and CSEB house models. However, the CSEB house model showed slightly better performance with temperatures below 80% comfort zone threshold. But CSB house model showed less thermal comfort as only 34.1% of the period was within the comfort zone.

Thermal comfort based on deterministic models

Examination of thermal comfort was performed through the psychrometric chart for each of the house models in an attempt to identify the most suitable house type and the results of which are summarized in Fig. 14. As shown in the Figure, for all three home models, the humidity was always above 40%, while the temperature was higher for the CSB house model. Even though the air temperature of the CSEB house model was less than the brick house model, due to the high humidity observed, there was a higher number of points with a PMV scale of + 1.5 (warm)

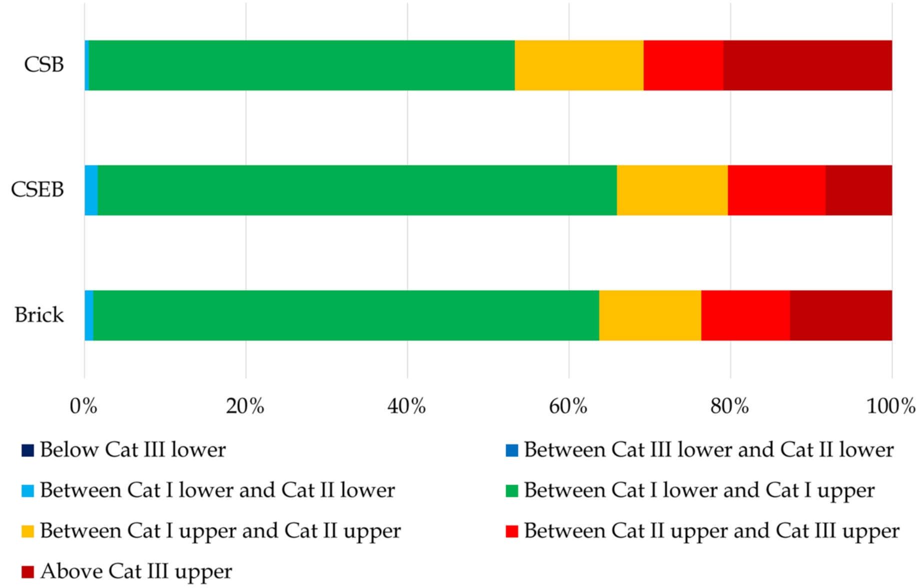


Fig. 12 Percentage of period lies within BSEN16798 thermal comfort categories

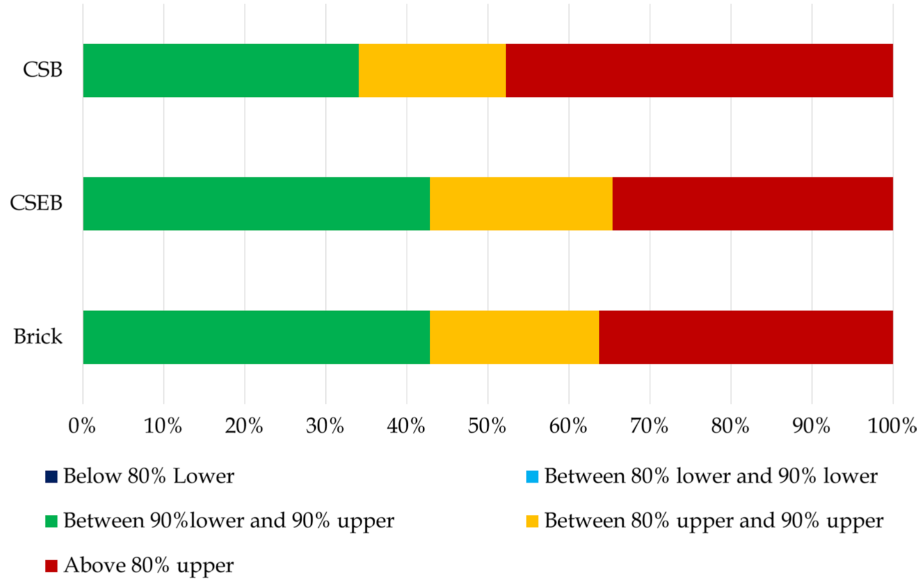


Fig. 13 The percentage of period lies within ASHRAE thermal comfort categories

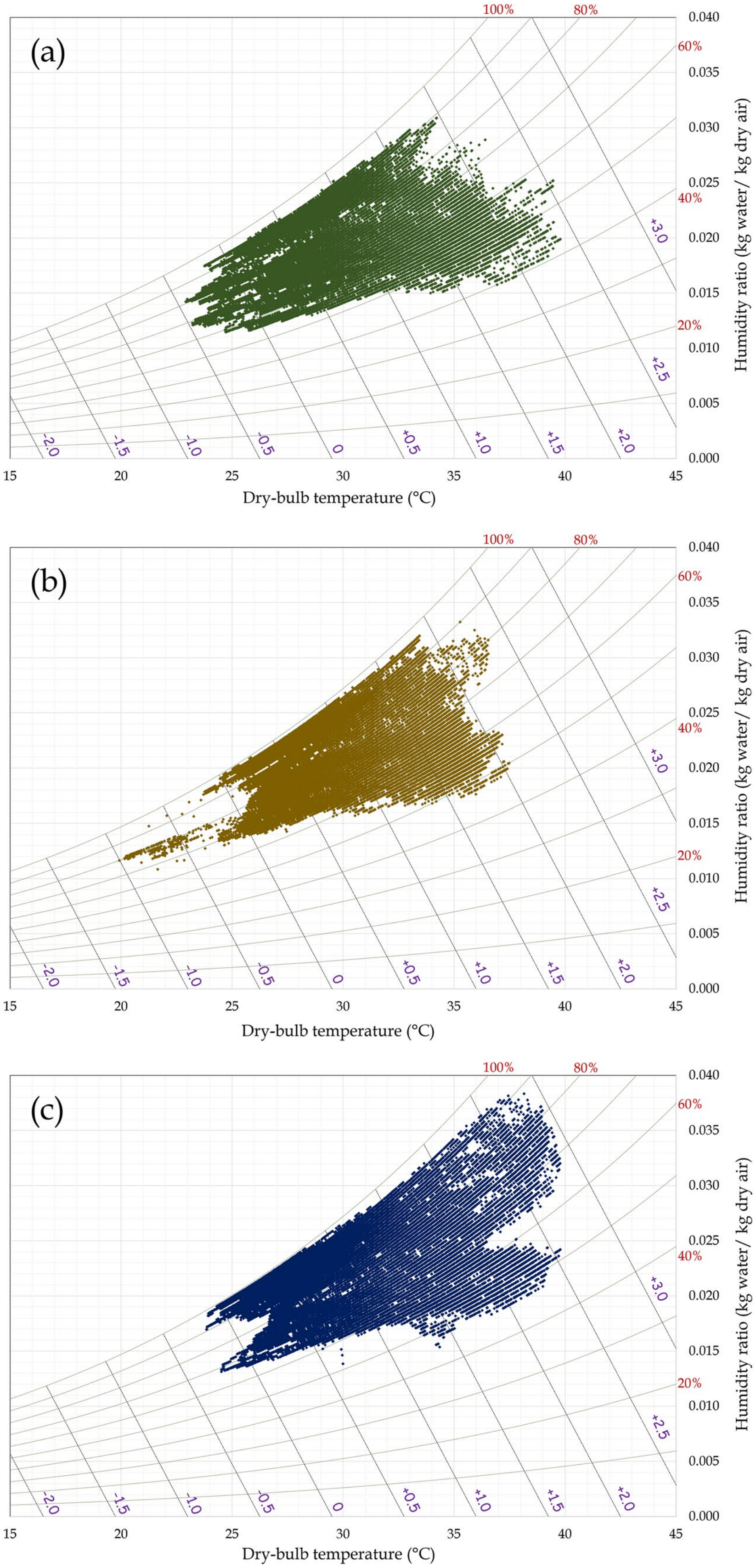
or above. It was observed that there were a few points less than PMV scale -0.5 (slightly cool) for the CSB house model. On other hand, there were several points more than the PMV scale of $+2.5$ (Hot) observed for CSB house models.

Thermal comfort for the combination of air temperature and humidity of each house model is presented in Fig. 15. The brick house model showed better thermal comfort with 37.2% of the recorded hours in the natural comfort zone (PMV scale -0.5 to $+0.5$), where, it was 6.5% and 9.1% more than the CSEB and CSB house models, respectively. In the meantime, the CSB house model showed 2.7% of the recorded hours in the hot zone (PMV scale more than $+2.5$).

Summary of thermal comfort performance of house models

Comparison of thermal comfort of these house models was conducted using steady-state, adaptive and deterministic thermal comfort models. The level of thermal comfort of three house units according to different methods is summarized in Table 3. When steady-state and adaptive thermal comfort models were used for evaluation, CSEB house models showed better thermal comfort. However, when the deterministic thermal comfort model was adopted for evaluation (a combination of air temperature and humidity considered here), the brick house model performed better.

Fig. 14 Temperature and humidity data on psychrometric chart for house models **a** Brick, **b** CSEB and **c** CSB



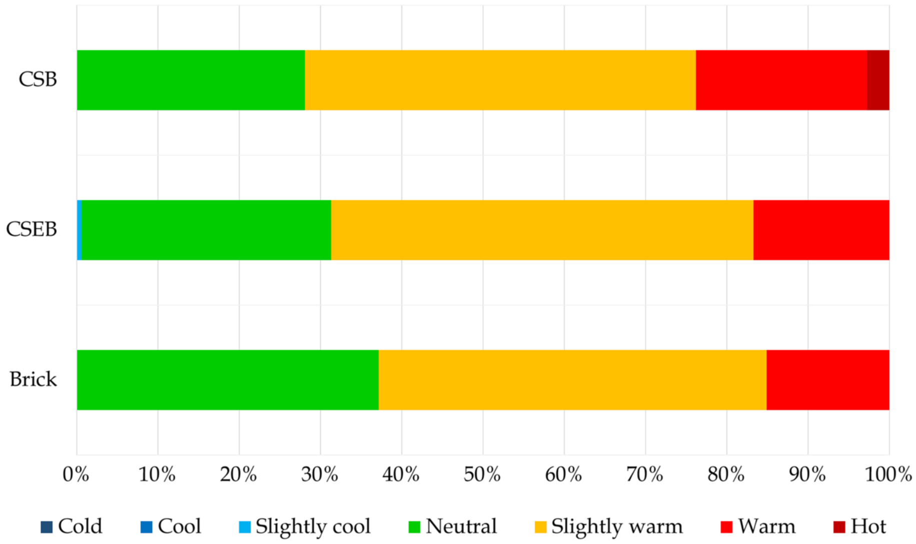


Fig. 15 Percentage time that measured internal temperatures and humidity of the house models lie within various thermal comfort categories

Table 3 The percentage recorded hours that lie within various thermal comfort categories

Comfort model	Standard/reference	Criterion	Brick	CSEB	CSB
Static	CIBSE Guide A	$T_{op} < 28$ °C	34.9	35.5	32.7
		$T_{op} < 31.5$ °C	67.7	69.9	64.0
		20% < Humidity < 80%	59.0	47.5	42.7
Adaptive	BS EN 16,798 (normal level expectation)	$T_{max} = 0.33\ T_o + 21.8$ $T_{min} = 0.33\ T_o + 14.8$	76.4	79.7	69.2
	CIBSE TM52	$T_{max} = 0.33\ T_{rm} + 21.8$ $T_{min} = 0.33\ T_{rm} + 15.8$	61.0	63.2	54.4
	ASHRAE 55	$T_{max} = 0.31\ T_o + 21.3$ $T_{min} = 0.33\ T_o + 14.3$	63.7	65.4	52.2
Deterministic	ASHRAE 55	PMV between − 1 to + 1 (slightly cool to slightly warm)	64.4	61.7	56.8

Conclusion

Thermal comfort of three different masonry materials (fired-clay brick, cement stabilized earth block, cement-sand block) used for house construction, were analyzed using small-scale house models. Temperature and humidity data were measured throughout the three months. Based on the results, the following conclusions are drawn:

- House model with CSEB can significantly reduce the conduction heat gain in the house as a result of the decrease in room air temperature. On the other hand, CEB can only impart limited control on the reduction of indoor air temperature.
- The brick and CSEB house models have a longer time lag and a lower decrement factor compared to CSB house model.
- When thermal comfort was analyzed based on adaptive criteria, both house models with CSEB and fired-clay brick showed similar thermal comfort levels while warm discomfort induced by the house model with CSB was about 10% higher than that of the other two house models.
- When thermal comfort analyses were based on deterministic criteria, house with fired-clay brick showed better thermal comfort level while warm discomfort induced by this house model was 2.7% and 7.6% less than a house model with CSEB and CSB, respectively.
- It can be concluded that a wall constructed with fired-clay brick and CSEB can reduce energy consumption associated with thermal cooling of the house and make houses more energy-efficient.

Finally, it is worthy to mention that the study limited the thermal comfort comparison of the scale model, analysis of full-scale model or real house with openings is recommended for future study to understand overall thermal comfort of the housing material.

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Code availability Not applicable.

Declarations

Conflicts of interest The authors declare that they have no conflict of interest.

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