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ORIGINAL RESEARCH

Characterising thermal behaviour of buildings and its effect on urban heat island in tropical areas

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Abstract

The heat island phenomenon in major cities is partly due to the excessive use of concrete and brick, which causes many problems regarding thermal comfort and energy expenditure. The thermal behaviour of the envelope wall material depends on its density, heat capacity, and thermal conductivity, and its effect on the heat island intensity (HII) is reported in this paper. Experiments and simulations were carried out on the four most popular building materials: brick, aerated concrete, wood with glass-wool insulation, and glass fibre-reinforced concrete with glass-wool insulation, with each material having a dimension of 1 m × 1 m. Experiments to analyse the thermal behaviour of the wall materials were performed by exposing each material to heat radiation from 2 × 1000 W halogen lamps for 4 h, followed by 4 h of cooling. The HII simulations were carried out in a simple urban kampong in a tropical area using Energy2D software. Heat flow analyses confirmed the thermal behaviour of the four walls, which can be categorised into two types: heat storage of block wall (BW) type and heat flow inhibition of insulated sandwich wall (ISW) type. The BW type showed 0.32 °C higher indoor air temperature than the ISW type, while the HII simulation showed ISW to be 0.74 °C higher than BW; however, both types increase the intensity and need mitigation treatment. The results of this study are important for the technological approach for dealing with local warming to lower the energy expenditure of poor people in an urban area.

Keywords Urban heat island · Thermal behaviour · Block wall type · Insulated sandwich wall · Urban kampong

List of symbols

ρ	Density
c	Specific heat
κ	Thermal conductivity
ρ_{avg}	Average density
c_{avg}	Average specific heat
κ_{avg}	Average thermal conductivity
T_{so}	Outer surface temperature
T_{si}	Inner surface temperature
T_{m1}	Temperature of the core wall at a depth of 2.5 cm
T_{m2}	Temperature of the core wall at a depth of 7.5 cm
T_{m3}	Temperature of the core wall at a depth of 12.5 cm
P_{so}	Heat flow at outer surface
P_{m1}	Heat flow at a depth of 2.5 cm
P_{m2}	Heat flow at a depth of 7.5 cm
P_{m3}	Heat flow at a depth of 12.5 cm
P_{si}	Heat flow at inner surface
T_{ao}	Outdoor air temperature
T_{ai}	Indoor air temperature
T_{ac}	Outdoor air temperature above the canopy layer

Introduction

In the past few decades, the construction industry has played a major role in the use of building materials that are currently in use [1, 2]. Deterioration of air, water, and soil environment quality due to pollution is difficult to avoid, and it significantly affects the quality of human life [3]. Building materials have also contributed to the destruction of the urban thermal environment and increase in energy consumption [4, 5]. In general, high-performance buildings have been reported to have appropriate material selection with regard

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Table 1 Thermal properties of common building materials

Material	Density		Specific heat		Thermal conductivity	
	ρ (kg/m^3)	Ref.	c [kJ/(kg K)]	Ref.	κ [W/(m K)]	Ref.
Brick	1600–1800	[36]	0.879–0.974	[36]	~0.60–0.73	[34]
Concrete/cement plaster	2000	[36]	0.880	[36]	0.61	[34]
GRC	2000–2400	[37, 38]	~0.880	[37, 38]	0.8–2.8	[37, 38]
Gypsum	~700–800	[39, 40]	0.7–1.00	[39, 40]	0.25–0.31	[39, 40]
Aerated concrete	~500–850	[41, 42]	~1.0–1.256	[41, 42]	0.13-0.18	[41, 42]
Wood	~300–700	[36, 43]	1.3–2.4	[36]	~0.10–0.17	[43]
Multiplex	400–630	[43–45]	~2.1	[43–45]	0.11–0.19	[44]
Glass-wool	30–34	[46]	~0.84	[47]	0.03–0.06	[46]

to the embodied energy level and CO_2 emission [6], and operational energy studies have reported the role of three aspects, namely the building envelope [7], building type [8], and household appliances [9]. Energy expenditure is a real issue that is calculated and discussed in terms of the role of these three aspects. Household appliances and building type have been discussed in building envelope studies in relation with geographical and climatic aspects [10]. Besagni showed that the energy expenditure is influenced by the monthly weather condition or outdoor air temperature [11]. Subsequently, in a discussion on economic viability, energy saving was reported by Galvin, who recommended a retrofitting policy for energy conservation. It also discussed the addition of loft insulation and wall cavity, which were shown to have a significant influence on energy expenditure [12]. The retrofitting policy, as a response to the energy crisis and environmental quality deterioration, is very relevant to old and conventional buildings, for example, the addition of insulation on the external wall [13]. In these cases, the retrofitting program for houses is driven by the energy expenditure and CO_2 emission from fuel energy consumption. From a different perspective, old and conventional buildings should also be retrofitted to respond to the deterioration of the microclimate such as local warming. This issue of local warming or heat island (HI) is undesirable in tropical areas where the cooling energy expenditures are very relevant for slump and low-cost housing.

The phenomenon of urban heat island (UHI) was first reported by Howard [14, 15]. Studies on the UHI phenomenon in tropical areas are very limited, and hence the UHI mitigation knowledge is limited as well. Specifically, the use of block type building materials (such as brick and concrete), which have high thermal capacity, is believed to be the main cause of this phenomenon [16, 17], in addition to various other factors such as reduced vegetation and the increased use of motorised vehicles [18, 19]. The existence of buildings causes HI in several ways, both direct and indirect, for example, the embedded energy and CO_2 emission of the building material, the operational energy for indoor air conditioning, warm air emission from air-conditioned rooms/buildings, and the direct heat release from building envelope materials (in conventional brick wall buildings) [16].

Several mitigation strategies have been implemented to reduce the UHI. In general, the discussions on UHI are focused on the effect and intensity of the UHI. Yang stated that UHI has a more serious implication in tropical and warm areas with regard to comfort, health [20], and energy consumption [21], while Aflaki and Nuruzzaman stated that urban greenery is the most effective strategy for mitigating UHI [22, 23]. Strategies related to the building component include the implementation of cool pavements and green roofs [24, 25], shading design for buildings and open spaces [26, 27], controlling albedo with a reflective surface for unshaded areas [28, 29]. Currently, numerous new building materials have been proposed as alternative green materials, including lightweight concrete, insulated metal panels, and insulated wood panels [30]. The concept of energy balance, as stated by Dernie, is a very potential concept for controlling the microclimate, which has been previously unrecognized in the era of brick wall buildings [31]. This includes the use of phase change materials (PCM) that can store the sensible and latent heat around its melting temperature with its application areas being the envelope, roof, floor, or walls of the building [32].

Each building material has a unique thermal characteristic. Block type building materials such as brick and concrete have a large density (ρ) and smaller specific heat (c) compared to aerated concrete and other materials such as wood. This value determines the amount of heat a material can store for every 1 °C rise in temperature. In addition, the thermal conductivity (κ) of building materials affects the rate of heat distribution in materials [33], which in turn affects the thermal behaviour of the buildings [34, 35]. Table 1 shows the density, specific heat, and thermal conductivity values of some commonly used building materials.

Additionally, the average density, specific heat, and thermal conductivity of the sandwich walls can be calculated by the rule of mixture formulas:

$$\rho_{\text{avg}} = \frac{\sum_{i=1}^{n} \rho_i \cdot d_i}{\sum_{i=1}^{n} d_i}, \tag{1}$$

$$c_{\text{avg}} = \frac{\sum_{i=1}^{n} m_i \cdot c_i}{\sum_{i=1}^{n} m_i}, \tag{2}$$

$$\kappa_{\text{avg}} = \frac{\sum_{i=1}^{n} d_i}{\sum_{i=1}^{n} \frac{d_i}{\kappa_i}}, \tag{3}$$

where ρ_{avg}, c_{avg}, and κ_{avg} are the average density, specific heat, and thermal conductivity of the wall, respectively; ρ_i, c_i, and κ_i are the density, specific heat, and thermal conductivity of the building material used for the wall, respectively; and m_i and d_i are the mass and thickness of the building material, respectively.

The amount of sensible heat stored by a wall is given by

$$Q = mc\Delta T, \tag{4}$$

where m is the mass, c is the specific heat, and ΔT is the temperature difference between the wall and its environment. The wider the temperature difference between the building and air is, the higher the heat absorption and release.

The thermal characteristic of each building material can be recognised as its thermal behaviour in response to the daily temperature fluctuation and weather conditions. The thermal behaviour of a building is also affected by its architectural design aspect such as the direction of the wall, material composition, etc., [16]. The accumulative effect of building thermal behaviour in a district, which results in the HI phenomenon, is influenced by the urban form, physical characteristics, and regional functions [48, 49], and the role of water bodies, vegetation, greenery composition in HI mitigation was discussed by Yang [18]. Thermal behaviour studies of a building or a district is very limited; the path of direct and indirect influences on the net thermal emission was mapped by Stone [50]. The area function is closely related to the shape of the building. Urban kampongs are generally composed of one-storey buildings with a small distance between buildings. In the morning and evening, the shadows of the buildings overlap each other, but in the afternoon, they do not. A building in an urban kampong has a proportion of horizontal mass. Unlike the central business district (CBD), which contains many medium-rise buildings, the proportion is more vertical. The difference in physical characteristics of the area produces a difference in the thermal behaviour and heat island intensity (HII).

In this study, the thermal behaviour of building materials and their effects on the HI phenomenon in a high-density slump residential in an urban area, which is known as an urban kampong, are demonstrated. This characteristic is chosen because it is dense enough to demonstrate the effect of the building material. Four types of walls are chosen, namely brick, aerated concrete, wood with glass-wool insulation, and GRC with glass-wool insulation, which are commonly used materials. This study is based on the studies of heat flow and thermal behaviour of common wall materials by Andoni and Thomas [51, 52]. This study shows a direct and measurable effect for the impact of various building materials on the environment, especially the HII in a common dense residential area in a developing country that is situated in a tropical area. The experimental data and simulation are used to study the thermal dynamic behaviour of walls and its effect on an urban kampong area. We argue that wall materials have a strategic role in conditioning both the HI phenomenon and indoor thermal environment. The industries of building materials and construction may be economically affected by the green issues of energy consumption and CO_2 emission. More than that, the urban HI phenomenon could be controlled by controlling the thermal behaviour of buildings.

Methods

This study experimentally demonstrates the different thermal behaviours of common wall materials during the heating and cooling periods. The heat flow characteristic is obtained from the wall temperature profiles. Mathematical and digital modelling using Energy2D [53] are performed to visually demonstrate the heat flow and thermal behaviour. The model developed using Energy2D is also validated by comparison with the results of the experimental study. Finally, the same software is used to predict the HII of the urban kampong.

The thermal behaviour characterisation was carried out on four types of walls with a dimension of 1 m × 1 m. The four walls are as follows: (1) brick, (2) aerated concrete, (3) wood with glass-wool insulation, and 4) GRC with glass-wool insulation (Fig. 1). Heat exposure was provided by 2 × 1000 W halogen lamps, involving 4 h of heating, followed by 4 h of cooling, with each period resembling the case of reception of solar radiation from 08:00 AM to noon and noon to 04:00 PM (Fig. 2).

The laboratory measurement method used to study the thermal dynamic behaviour of the wall is adopted from Aversa [54]. Originally, Aversa used an infrared thermography method to investigate the thermal behaviour of an opaque building component. In this study, we use a direct temperature measurement method, which not only depends on the surface temperature but also on the inside layers of the material. This method provides more accurate results and is more appropriate for the dynamic thermal behaviour, since it can provide the temperatures inside the wall. Thermal behaviour measurements are performed to evaluate the outer surface temperature (T_{so}), inner surface temperature (T_{si}), and the temperature of the core wall (T_{m1} at a depth of 2.5 cm, T_{m2} at a depth of 7.5 cm, T_{m3} at a depth of 12.5 cm) using a thermocouple data logger with an accuracy

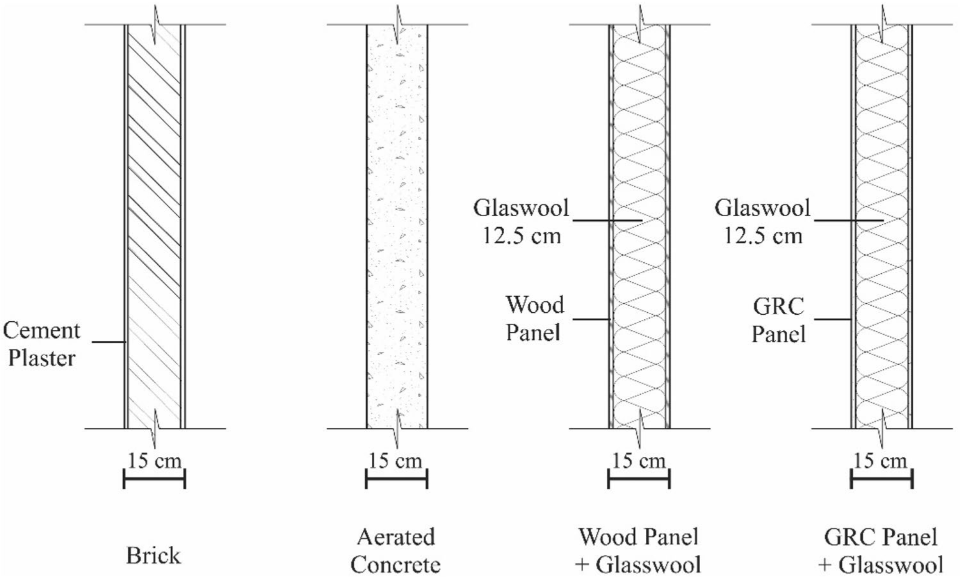


Fig. 1 Four types of walls and their cross-sectional dimensions

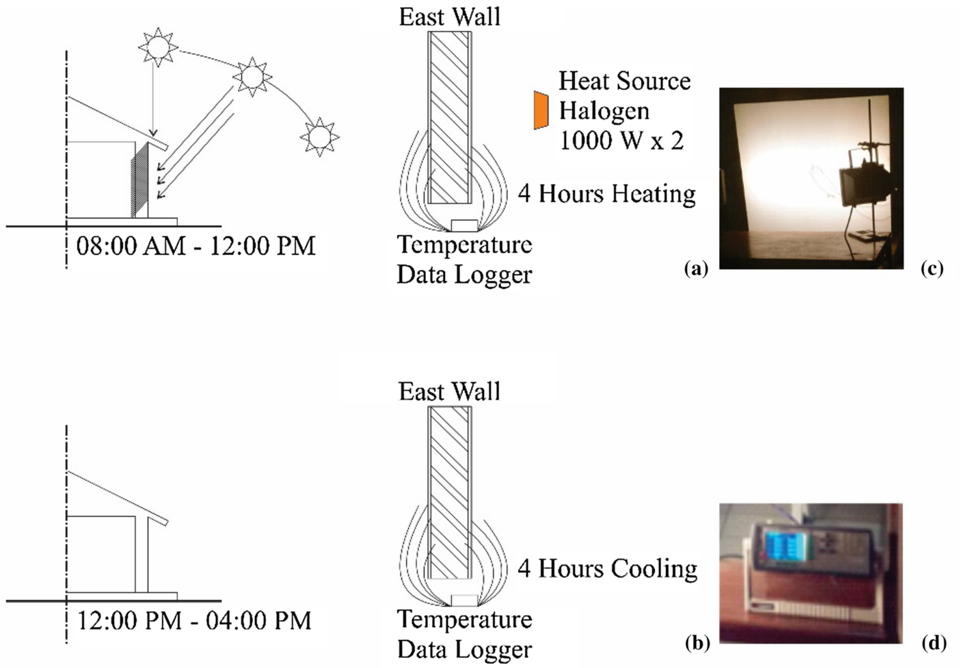


Fig. 2 The wall temperature measurement to represent **a** the exposure to sun during the day and **b** the cooling period; **c** halogen lamp and **d** temperature data logger

of 0.2% + 1 °C, at fixed time intervals of 5 min (Fig. 3). The measurement for each type of wall was repeated three times to ensure data repeatability. The results demonstrate the effect of heat flow on the wall during the heating and cooling processes.

To study the thermal dynamic behaviour of each type of wall, mathematical modelling was performed on the heat flow for the walls. Each wall was segmented into several tiny layers, each with a thickness of 1 cm. The dynamic heat flow can be defined by Formula (5) as follows:

$$P = \frac{\Delta q}{\Delta t} = A.d.\rho.c.\frac{\Delta T}{\Delta t}, \tag{5}$$

where d is the segmented wall thickness (m), ρ is the average density of the wall (kg/m^3), c is the specific heat of the building material [kJ/(kg K)], and $\frac{\Delta T}{\Delta t}$ is the temperature difference per second of the wall material (K/s). Thus, we define the density, specific heat, and temperature difference for each layer, enabling the power distribution for heat flow to be calculated. The temperature difference (ΔT) and rate of temperature change ($\Delta T/\Delta t$) in this calculation are taken from the measurement results. The values of heat flow in different layers associated with the temperature measurement are P_{so}, P_{m1}, P_{m2}, P_{m3}, and P_{si}.

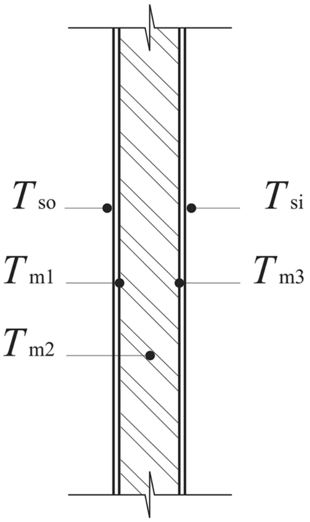


Fig. 3 The positions of T_{so}, T_{m1}, T_{m2}, T_{m3}, and T_{si} on each type of wall along its cross-section

In the simulation study of the wall materials using Energy2D, a boundary temperature of 20 °C and a radiation heat source temperature of 1750 °C were used, thus resembling the laboratory experimental setup. The input data of the wall model were based on the references (Table 1). On the sandwich walls, these values are the average values for GRC or external multiplex and glass-wool materials. Using the data in Table 1 and calculations with Eqs. (2)–(4), the density, specific heat, and thermal conductivity values of the investigated sandwich wall materials (Fig. 1) are 132 kg/m^3, 1.867 kJ/(kg K), and 0.045 W/(m K) for the multiplex glass-wool sandwich, and 386 kg/m^3, 0.875 kJ/(kg K), and 0.045 W/(m K) for the GRC glass-wool sandwich, respectively. The position of temperature sensors is similar to that in the experimental setup. For validation, the result of heat flow from the Energy2D simulation and direct measurement were compared using the mathematical model of the segmented wall method.

Additionally, the effect of these building materials on an urban kampong was demonstrated through the Energy2D simulations. To simulate an urban kampong environment, three one-storey houses were used, each at a distance of 2 m apart, which is a common feature of urban kampongs (Fig. 4). We set the width and height of the kampong environment model as 15 × 15 m for the observable air environment, and the temperatures of all the boundaries were set to 15 °C. The environmental settings are limited to the software capabilities in these dimensions, hence, the modelling closely resembles actual conditions. The effect of each wall material is studied by varying the wall material density, thermal conductivity, and specific heat.

The thermal behaviour of the building was formulated from the parameters of heat flow and heat exchange with air. In the HI simulation, the effects of different wall materials on the outdoor air temperature (T_{ao}) and indoor air temperature (T_{ai}) were measured at 150 cm above floor level.

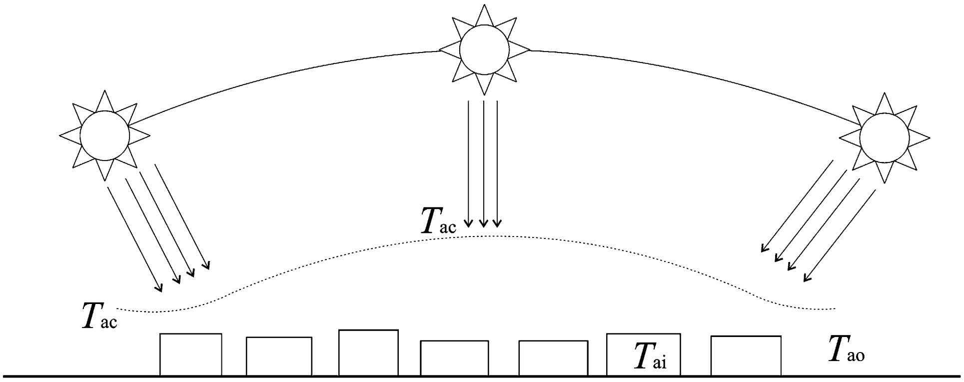
Results and discussion

Profiling wall temperature

The wall temperature profile is obtained by measuring the wall surface temperature (T_{so} and T_{si}) and the internal temperature of the wall (T_{m1}, T_{m2}, and T_{m3}) and is shown in Fig. 3. In the heat radiation exposure process, T_{so} of the wood wall increased much faster and reached the highest temperature, followed by those of GRC, aerated concrete, and brick walls. The surface temperature (T_{so}) of the multiplex wall is the highest because of the lowest multiplex density. This means that the received heat energy is used to increase its surface temperature. Unlike the GRC material (which has higher density), its temperature rise is not as high as that in multiplex wall. Brick walls are the densest, hence, the heat energy is mainly absorbed and transferred to the centre of the wall, meaning that the temperature rise is the slowest.

As shown in Fig. 5, during the heating process, the temperature inside the wall surface (T_{si}) increases for all types of walls. During cooling, there is a decrease in temperature

Fig. 4 Simulation concept for the effects of wall materials on the air temperature of a dense area



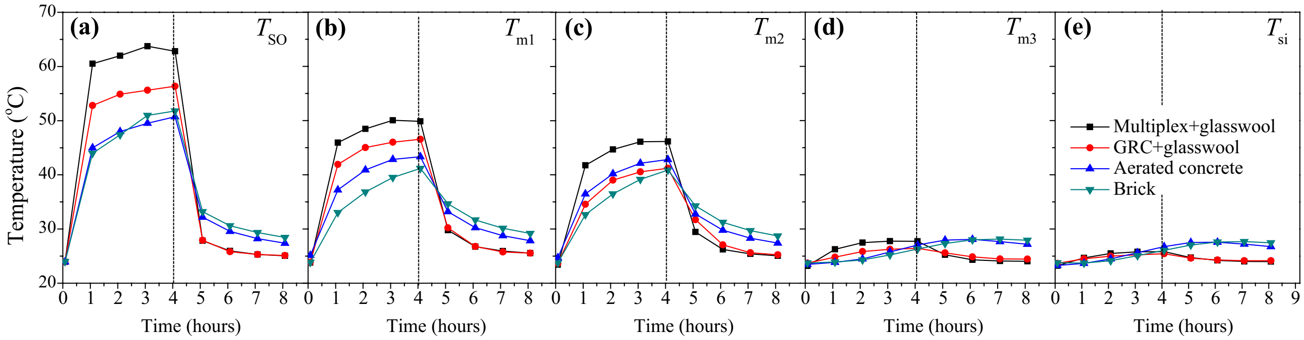


Fig. 5 Temperature evolution of: **a** T_{so}, **b** T_{m1}, **c** T_{m2}, **d** T_{m3}, and **e** T_{si} during the heating and cooling processes. The error bars represent the standard deviation values from three repetitive measurements. (Improved from Andoni et al. [52])

on the multiplex wall and GRC, but an increase in T_{m3} and T_{si} still occurs in the aerated concrete and brick walls. This phenomenon indicates that the aerated concrete and brick walls can store heat energy and pass it to the interior surfaces of the wall. For graph clarity, the data are presented hourly.

The temperature at the centre of a wall experiences the same phenomenon. The glass-wool temperature rises rapidly compared to the temperature of the aerated concrete and brick materials. The temperature of the glass-wool is also higher than that of the brick. The density and specific heat factors show a dominant role. This means that the brick and aerated concrete (with greater density) tend to absorb the heat and store it, hence, the temperature does not increase significantly.

The comparison of temperatures at each measuring point for a heating period of 4 h showed that the difference in the outside and inside temperatures was the greatest in the multiplex and GRC walls, while the brick walls and aerated concrete exhibited the smallest value. This result confirms that the multiplex and GRC walls behave in a similar manner to insulated sandwich walls (ISW). On the other hand, the brick and aerated concrete walls show almost the same thermal behaviour as the block wall (BW) (Fig. 6).

In the cooling process (Fig. 7), the temperature reduction of the block wall type tends to be slow, in contrast with the sandwich type wall, which cools down quickly. The temperature of the block wall is also higher than that of the sandwich wall after 4 h of cooling.

The centre of the block wall also has a higher temperature than its surface. This corroborates the interpretation that the block walls store heat, while the sandwich walls do not. This can be very useful (for example) in sub-tropical areas [7]. For tropical regions, heat-storage type walls have the potential to cause severe HI phenomena [38, 55]. The heat accumulated during the day on the walls of the buildings in the tropics is released into the air during both day and night, which will accumulatively raise the air temperature of the region over a long period of time. However, the use of an indoor heat-storage type wall will provide a cooler and more comfortable interior environment [56, 57].

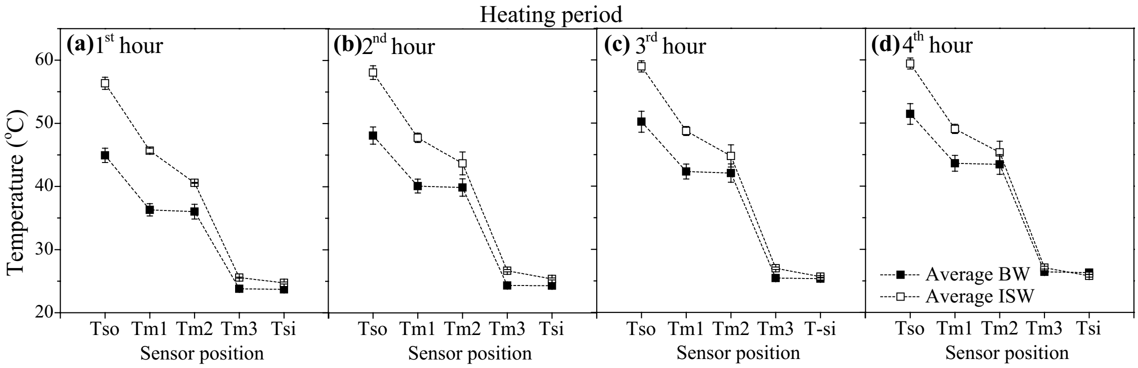


Fig. 6 Changes in temperature at each measuring point for the: **a** 1st hour, **b** 2nd hour, **c** 3rd hour, and **d** 4th hour of heating on two types of walls (improved from Thomas et al. [51])

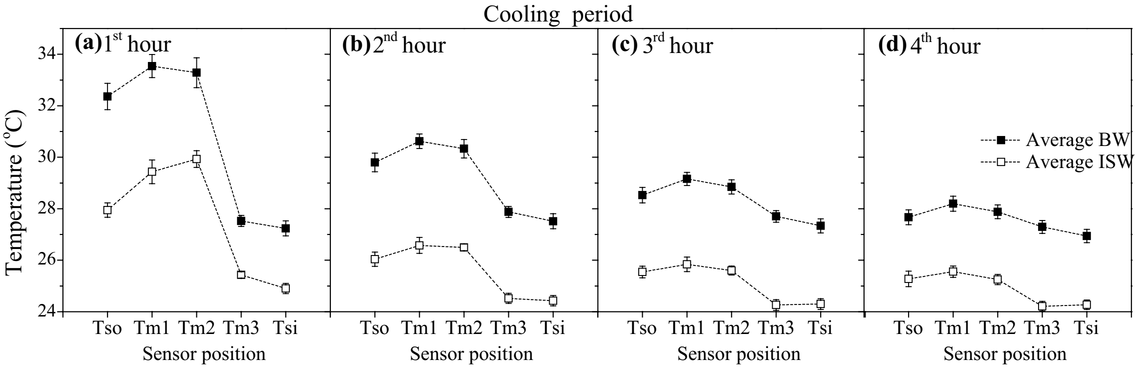


Fig. 7 Changes in temperature at each measuring point for the: **a** 1st hour, **b** 2nd hour, **c** 3rd hour, and **d** 4th hour of cooling on all types of walls (improved from Thomas et al. [51])

Heat flow analysis

The analysis of heat flow using Eq. (5) gives different heat flow patterns each hour during both the heating and cooling processes. With regard to the block wall, a large amount of heat flows from the outer surface and propagates inwards. During the cooling period, the heat stored in the inside of the wall is quite large.

In the case of a sandwich wall, heat flow does not occur in most parts of the wall during both the heating and cooling periods (Fig. 8). Thus, it can be understood that sandwich walls have a thermal behaviour that inhibits heat flow.

The heat flow pattern on the block wall and insulated sandwich wall are shown by the Energy2D simulation results (Fig. 9).

The simulation results of heating show that the surface temperature of the sandwich wall is higher than that of the brick wall, as the heat flow is inhibited by the insulation layer on the sandwich wall. This phenomenon is confirmed from the observation that the indoor surface temperature of

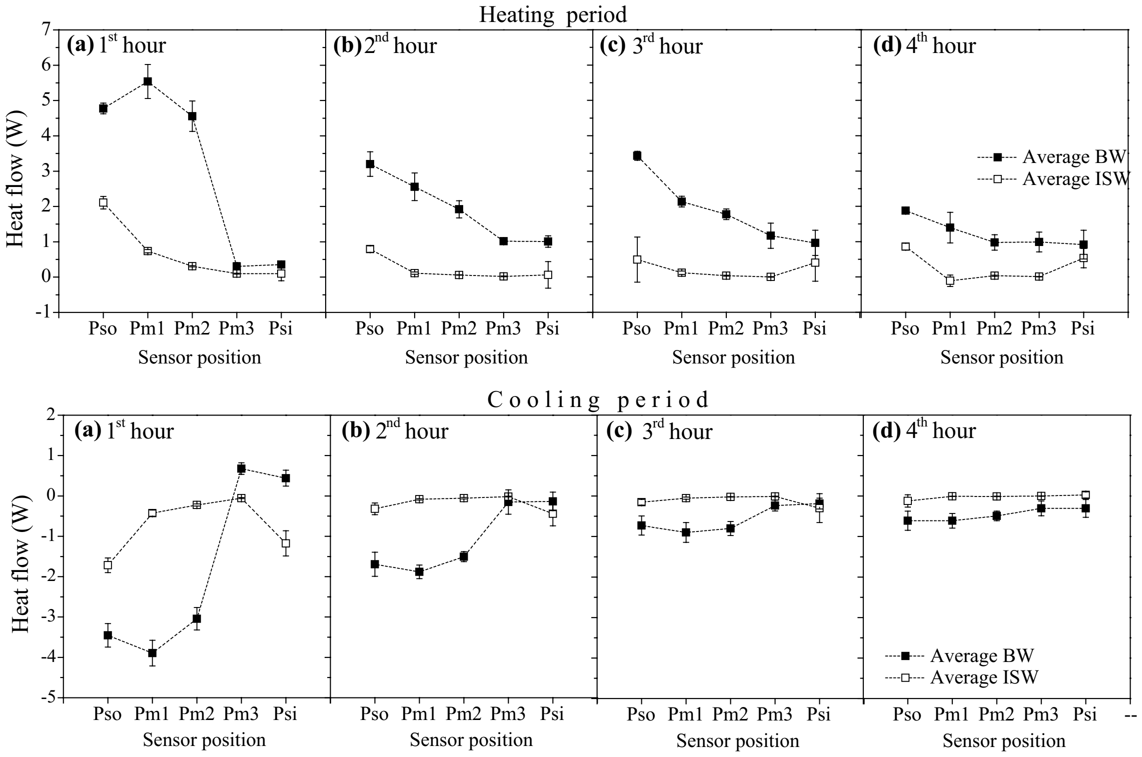


Fig. 8 Comparison of heat flow in two wall types during the first 4 h of heating (above) and second 4 h of cooling (bottom) (improved from Thomas et al. [51])

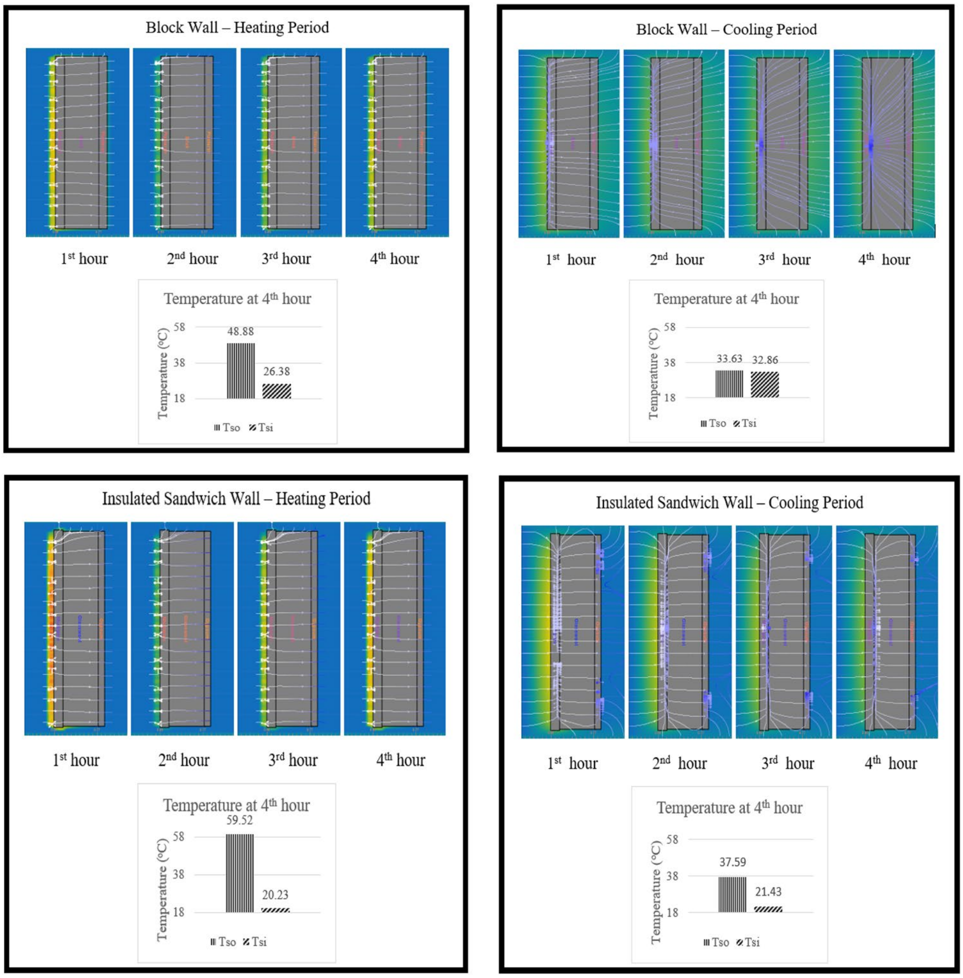


Fig. 9 Simulation results showing the pattern of heat lines due to the heating and cooling on the block walls (above) and sandwich walls (bottom). The chart below each graph represents the outside and inside surface temperatures at the end of the heating (4th hour) and cooling (8th hour) processes

the sandwich wall is lower than that of the block wall after heating for 4 h. In the cooling process, the heat release of the brick walls occurs on the outer and inner surfaces from the beginning of the cooling process, with a tendency to release heat into the room. This effect increases with time, whereas on the sandwich wall, the heat release only occurs outwards. This is confirmed from the higher indoor surface temperature of block wall than that of sandwich wall after 4 h cooling.

Based on this heat flow analysis, it can be seen that brick walls have a negative effect on the heat release during the day (to both the outer and inner spaces), while the sandwich wall has a negative impact only on the outer space. The simulation results of the brick wall are consistent with the experimental results (Fig. 10).

Effect of building thermal behaviour on air temperature and heat island intensity

In the experiment and digital simulation results, the two types of BW and ISW materials show different effects on the air temperature near the outdoor and indoor near surfaces. The air temperature near the outside surface of the BW is lower than that of ISW during the heating period. This phenomenon indicates the role of heat storage in the case of BW (Fig. 11). The air temperature near the inside surface of the BW was higher during the cooling period, which indicated the heat release process.

Urban kampongs are widely found in large cities in developing countries. Urban kampongs generally have a horizontal and high-density characteristic with narrow inter-building distances consisting of one-storey buildings [3, 16].

In this study, a simulation of the application of block wall and insulated sandwich wall in urban kampong areas was carried out. As stated earlier, the insulated sandwich walls are simulated as lightweight single materials with density values, thermal conductivity, and specific heat obtained from the average value of the constituent materials.

The Energy2D simulation in the area where the building uses block wall type envelope walls shows that the HII in residential areas is lower than that in the areas using multiplex walls with glass-wool insulation (Fig. 12). This is because the concrete and brick walls absorb heat and store it in the walls and rooms inside the building, while the

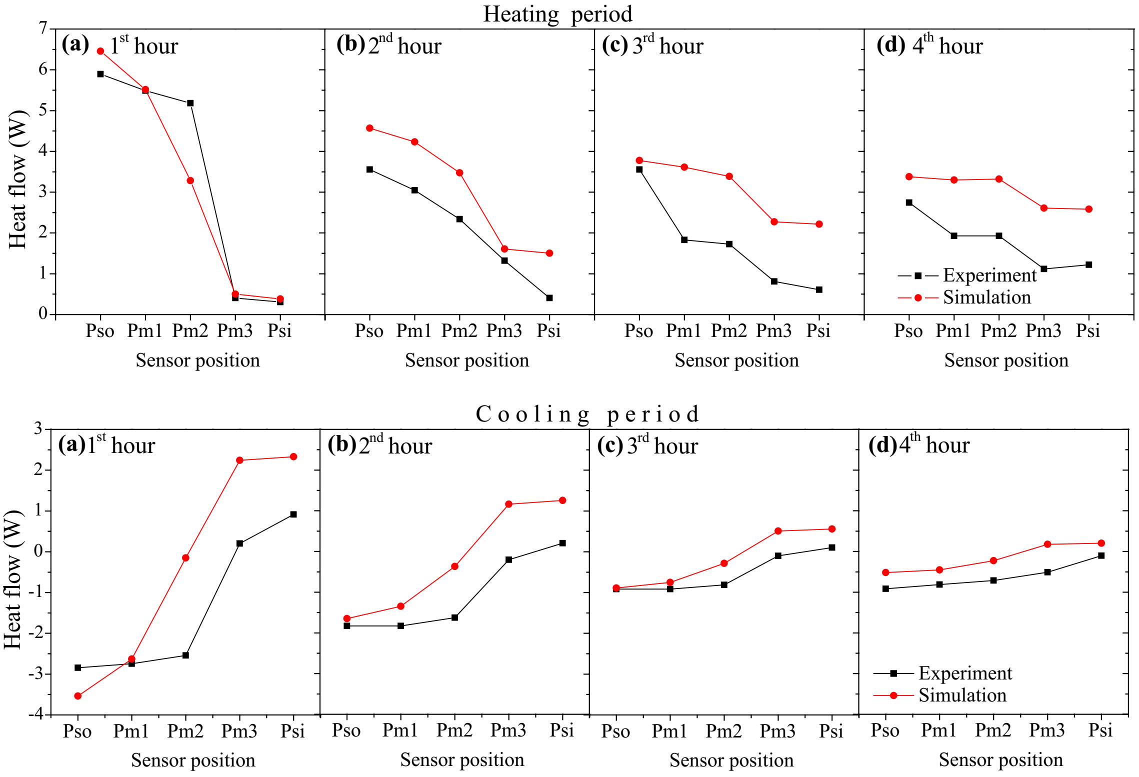


Fig. 10 Comparison of the experimental results and simulation results of heat flow in the heating (above) and cooling (bottom) processes on the brick wall

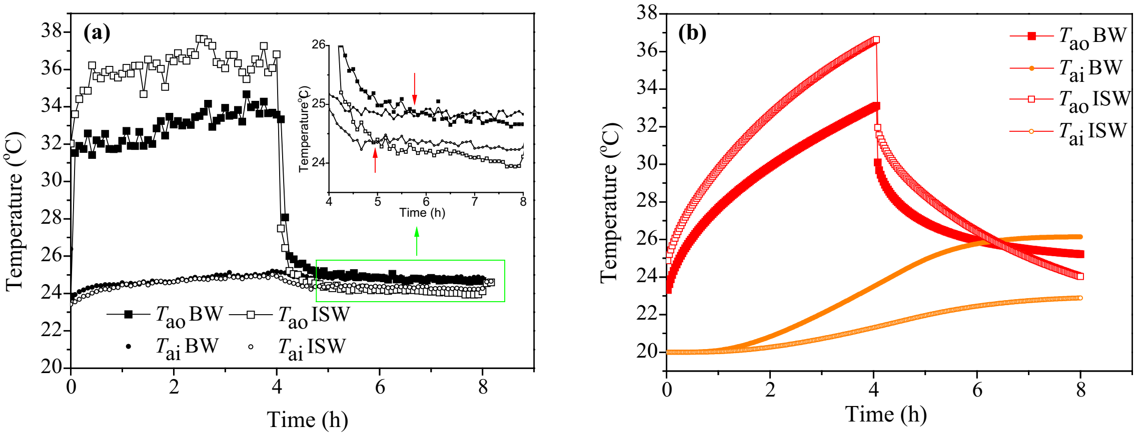


Fig. 11 The outside and inside air temperatures of BW and ISW resulted from the experiment (**a**) and simulation (**b**)

buildings with insulated sandwich walls do not store heat. The heat received by the multiplex wall cannot penetrate the wall, hence, it is released back into the outer air as infrared (IRE). This is in line with the multiplex wall heating and cooling simulation results shown in Fig. 9.

In Fig. 12, T_{ao} is the outdoor air temperature below the canopy layer, while T_{ac} is the outdoor air temperature above the canopy layer. The T_{ac} chart shows a stable temperature value, while the fluctuating T_{ao} is influenced by the solar cycle. A comparison with the T_{ac} shows that air temperature under the canopy layer (T_{ao}, T_{ai} in both regions) has the potential to cause high HII. Areas with concrete buildings exhibit the phenomenon of stored heat being released back after a while. The night air temperature in the rooms (T_{ai}) in these buildings is higher than the outside air temperature (T_{ao}) (Fig. 12, right above). The insulated wall buildings

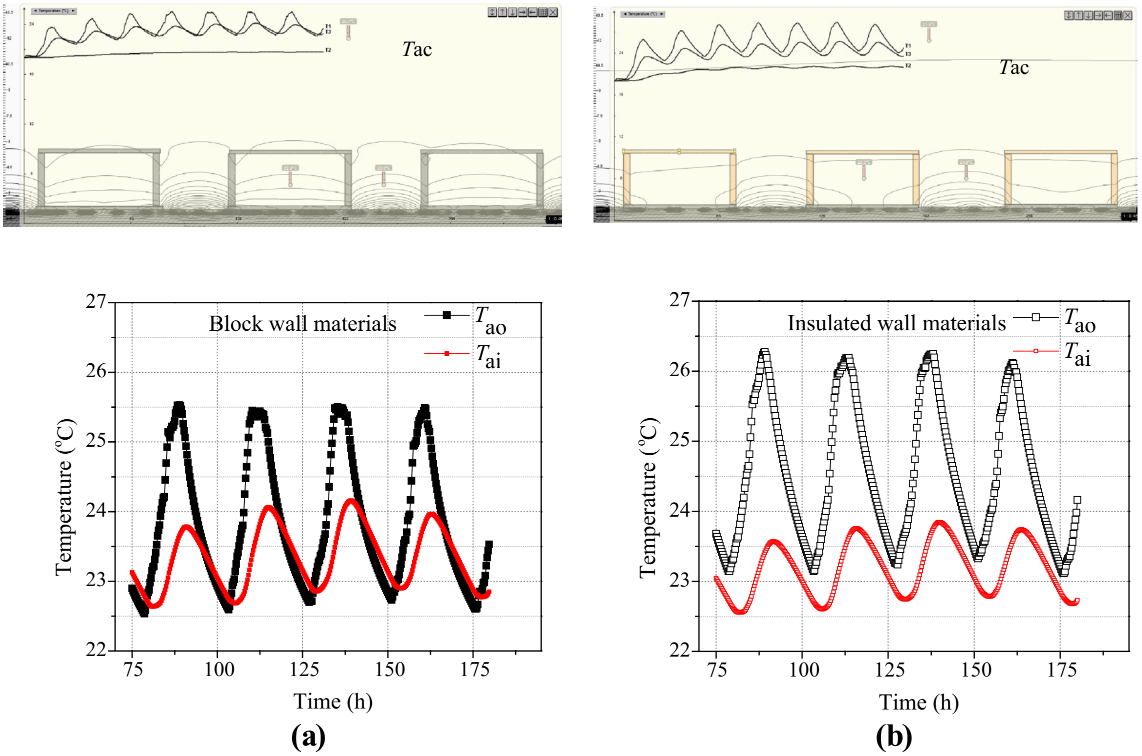


Fig. 12 Simulation process of urban kampongs (above) using **a** block wall type and **b** insulated wall materials, and their respective resulting temperature profiles (bottom)

have higher air temperatures due to the absence of heat absorption by the building masses. The heat received by the wall cannot penetrate indoors, because it is hampered by the glass-wool insulation. The difference between the maximum of indoor air temperature (T_{ai}) for block wall (BW) and the insulated sandwich wall (ISW) is about 0.32 °C, while the difference between the maximum of outdoor air temperature (T_{ao}) for the two types of the wall is about 0.74 °C.

Through this discussion, we would like to demonstrate several concepts that have been widely understood and add some new insights into the use of building materials. The role of building envelopes in an urban thermal environment has been explained by many experts [5, 58], and therefore many green building concepts have been presented [47]. The use of block type building materials such as concrete and brick has been reported [38] to have a negative influence on the HI phenomenon. Another idea suggests that buildings with multiplex walls and glass-wool insulation do not store heat, for example, brick and concrete. This concept, in general, is offered as an environmentally friendly concept because of its ability to suppress the cooling load in air-conditioning systems in buildings. However, the results of the study indicate that multiplex walls have a worse impact on the intensity of HI than brick walls. Sandwich walls with high thermal insulation trap the heat received from the sun on the outer surface, and the temperature rises faster than the surface temperature of the concrete. Thus, the air temperature around the building rises rapidly if the wall receives more sunlight. Therefore, the concept of insulated sandwich wall with high insulation is less acceptable as an environmentally friendly wall in terms of HII.

Both the block wall type and insulated walls adversely affect the outdoor thermal environment. Currently, buildings with highly insulated sandwich walls are becoming increasingly popular, because they lower the energy consumption and increase the thermal comfort [59, 60]. Moreover, the popularity of buildings with insulated sandwich walls is very reasonable because they are light, and the construction process is fast [61]; however, the use of this kind material has the potential to exacerbate the HII.

With regard to building material popularity, the delay effect of BW promises a comfortable daytime indoor air temperature, however, the delay effect causes an accumulative warmer impact on the outdoor air environment during nighttime. The conventional BW technology was very popular for a long time, however, it has the side effect of increasing the air temperature, which was not recognised before. After it was found that the BW type results in HI in tropical high-density urban areas, the ISW type was introduced as a better wall concept for cooler indoor temperature with lower energy consumption for air conditioning. The application of this concept is very relevant to the energy efficiency policy for the poor and has the potential to be a popular building type in tropical areas. The ISW is a kind of 'thermal renovation' that caused the BW type to be replaced by ISW type. The popularity of the ISW concept potentially has a direct rebound effect on the energy efficiency program, where people feel free to build air-conditioned rooms with the ISW concept [62]. In this case, the rebound effect not only deals with people but also with the construction industry sectors and policy makers of the built environment. The policy approach includes taxes to control both the demand and supply sides [63]. However, the technological approach of mitigation techniques should be complementary to the economic and energy policies [64]. The mitigation technology should be developed to balance the economic behaviour of the people. For example, in this case, both types of buildings require an appropriate mitigation technology. Insulation technology can reduce the heat gain from the solar radiation without increasing its surface temperature. Further studies are needed to formulate an HI mitigation technology that is appropriate for both building types. The supply side has greater responsibility than the demand side; however, both sides need a controlling regulation to deal with the rebound effect [63, 65].

The Indonesian regulation of Permen ESDM No. 13 Tahun 2012 [66] just regulates the electrical consumption of state buildings. The use of air conditioning (temperature and humidity setting) is regulated by Standar Nasional Indonesia (SNI 03-6572-2001 Tata Cara Perencanaan Sistem Ventilasi Dan Pengkondisian Udara Pada Bangunan Gedung) [67]. The regulation and standard of energy consumption are based on efficiency and rational principles of work safety, comfort, and productivity. The regulations control the air temperature setting (24–27 °C) and the operational hours. The Indonesian regulation of energy consumption (Intensitas Konsumsi Energi, IKE) is based on the national standard SNI 03-6196-2000 [68] for Prosedur audit energi pada bagunan Gedung, which standardises the procedures of energy audit on buildings. The IKE, which measures the electrical consumption per square metre of floor area in a year ($\mathrm{kWh/m^2.year}$), is not mandatory for private buildings. In the housing sector, the government regulates the classification of housing based on the room area, i.e., 21, 36, 45, 54 $\mathrm{m^2}$ for detached houses and multi-storey houses. This classification is based on their capability for paying instalments and the minimum income standard (MIS) [69, 70] of Upah Minimum Regional (UMR). Several problems of low-cost housing have been identified, for example, the building quality and distance to work. The poor house quality of low-cost housing increases the energy expenditure due to the thin roof thermal insulation, which affects life quality, health, comfort, and productivity. The distance problem of remote housing area for the poor increases the fuel expenditure. The low income, high cost issue (LIHC) exists in the housing industry in Indonesia, because for comfort, people in a small and low-quality house need more air conditioning than those in one with a higher quality building.

The energy poverty of Indonesia, which was reported by IESR (Institute for Essential Service Reform) [71], promotes the energy saving program in Indonesia. IESR has reported that many people live without electricity and fuel for daily life. Based on the Indonesian statistical bureau of BPS (Badan Pusat Statistik) 2010 [71], at least 22 million people or 19% of the total population live under the energy poverty line. According to a single indicator reported by Chen and Ravallion [72], people working in the informal sector in an urban area live under the poverty line with an income below 1$/day. The existing government policy for urban slums is to reform horizontal housing into a vertical housing. As an illustration of the energy consumption in urban slums in Indonesia, an energy survey on urban slums in Bandung Indonesia reported that people living in horizontal slums consume 15% more energy for lighting than they do in flats [73]. The study showed that the building quality of flats is better than detached houses, which resulted in controlled energy consumption.

The discussion of low-income people who utilize energy for comfort could be approached from the built environment side. The phenomenon of LIHC is real and exists everywhere, which proves the inappropriateness of the environmental technology used in developing the built environment. Conditioning the local environment such as the urban area has become a critical aspect for dealing with the problem of energy consumption. The existing building materials and technologies are still not suitable for the nature of environment and require changes in terms of quality. Local warming is a new phenomenon in urban areas due to both BW and ISW types, and it is necessary to have a mitigation technology for the thermal behaviour. The environmental technology aspect should be a proper parameter in defining the energy poverty line [74].

Conclusions

Urban buildings create a thermal environment around them. The results of this study show the importance of thermal behaviour on various types of building materials, which produce different effects on the HII. The buildings with block wall type store heat, which increases the HII after absorbing the heat from solar radiation. Conversely, buildings using insulated sandwich type walls act as heat inhibitors and increase the HII due to high surface wall temperatures. Thus, it can be concluded that the HII is a function of the specific heat, density, and thermal conductivity of the building materials used in the area. High-density walls such as brick and concrete store heat, causing a significant increase in HII during the afternoon. A sandwich wall that has an internal layer with a small thermal conductance causes the outside wooden layer to have a high surface temperature, which increases the HII either directly or without delay. To control the HII, an appropriate mitigation technology, which is in accordance with the thermal behaviour of the two wall types, is needed. The technological aspect of retrofitting the built environment should be part of the energy saving policy especially for the poor people, which directly impacts the urban local warming. This approach of technological thermal renovation should be part of the energy policy, and it should also be used for defining the energy poverty line. At present, it is necessary to study smart and low-cost insulation technology to reduce the HII. A technique that has great potential to reduce the HII is the application of one-way thermal insulation on the outer surface of the envelope wall. This insulation allows heat gain on the envelope wall but inhibits its reemission to the outside according to the phenomenon showed in this research.

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Compliance with ethical standards

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