J Wood Sci (2014) 60:117–126
DOI 10.1007/s10086-013-1383-x

ORIGINAL ARTICLE

Influence of wall composition on thermal environment of wooden houses

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Received: 2 April 2013 / Accepted: 22 August 2013 / Published online: 5 January 2014

Abstract This survey was conducted from 2005 to 2008 regarding the thermal environment of three types of experimental houses—a wood and mud composite wall type (Type WM), a mud wall type (Type M), and an insulated wall type (Type I). To reveal the influence of the wall composition of wooden houses on the indoor thermal environment, each experimental house was constructed on the same site. As a result, under natural indoor air temperatures, the monthly average indoor air temperature level and the time ratio of indoor air temperature surpassing the outdoor air temperature were in the following order: Type I > Type WM > Type M. Type WM exhibited the highest phase shift of air temperature, indicating that the insulation performance and heat capacity affect the phase shift of air temperature. The equalization of indoor air temperature through the suppression of the increase in the indoor air temperature of Type M is likely caused by low insulation performance and large thermal capacity. The time fluctuations in electric consumption by air conditioning and indoor–outdoor air temperature differences of each experimental house over 1 day indicated that a building's thermal load and the thermal capacity are related.

Keywords Thermal energy · Heat capacity · Electric consumption · Wooden composite wall · Thermal storage loop

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Introduction

Considering the social demands associated with global environmental issues, energy reduction in buildings has become an important topic. Increases in the insulation performance and passive design technology are anticipated as methods for reducing the energy consumed by air conditioning in the building sector [1]. In Japan, energy reduction standards have been revised [2], and the number of modern residences equipped with high-performance insulation is increasing. The amount of energy consumed through heating in Japanese residences is 25 % of the annual energy consumption, even in warm regions [3]; therefore, higher performing insulation would be effective against annual energy consumption. However, such improvements in the insulation performance include the risks of overheating and an increased cooling load during the summer in Japan's warmer regions. On the other hand, the thermal storage property helps prevent overheating during the summer. In the winter, it also helps maintain indoor air temperature due to heat stored during the day and heat dissipation at night.

In Japan, insulation performance of building walls has been evaluated in terms of thermal resistance. Therefore, the traditional architecture, which has large heat capacity due to mud walls or the combined walls of wood and mud, has been evaluated low in the viewpoint of insulation efficiency. However, in the aspect of fire resistance and aseismic performance, the Japanese traditional wood frame construction has come to be reviewed. For example, using mud walls with more than 40 mm thickness for outside walls with exposed timber columns, the 30-min fire-resistance standards [4] have been certified. The reevaluation of the excellent performance of mud walls makes it possible to design an external appearance of traditional architecture.

In recent years, reduction of environmental load through life-cycle assessment is highly evaluated and natural building materials come to the front.

Natural building materials such as mud and wood are used worldwide [5–7], and many elements such as walls composed of wood and mud are used in Japan's traditional wooden residences. The thermal conductivity of wood [8] and the thermal characteristics of wooden walls [9] have been reported. In addition, mud walls composed of multiple layers of mud, straw, bamboo, and wood were reported to exhibit significant heat storage capacity [10, 11], and their phase shift of thermal response and equalization of the daily range of indoor air temperature caused by thermal storage have been reported [12–15]. However, much of the existing research targets the buildings themselves and does not simultaneously compare the thermal environments of experimental buildings with various wall specifications. Since the indoor thermal environment of a residence is created and affected by parameters such as building specifications, room volume, climate, and the surrounding environment, it is difficult to comprehensively assess the indoor thermal environments of individual buildings.

This study reveals the influence of wooden-housing-wall structures on indoor thermal environments and assesses the energy reduction performance of housing made with natural building materials. Moreover, through an experimental model equipped with wooden board inside mud walls, the effect of wood on improvement in the thermal performance of house with mud wall is investigated. Three experimental buildings were constructed in the same region with identical parameters except for wall specifications, and simultaneous measurements were conducted for indoor and outdoor air temperatures and electric consumption by air conditioning (electric consumption). The three types of walls were composite wood and mud walls (Type WM), traditional mud walls (Type M), and insulated walls that are currently used widely (Type I). Yamasaki [16] measured the heat transmissions of such walls and reported the relationship between indoor–outdoor air temperature differences and indoor air conditioner energy consumption during the winter. In this report, the natural indoor air temperature when the air conditioner was not in use and the amount of energy to maintain a specific indoor air temperature was measured, and the influence of wall insulation performance and heat capacity on the indoor thermal environment was examined.

Method

Experimental house

Three experimental houses were constructed in the same area in Anjo City, Aichi Prefecture, Japan (E137°05′, N34°57′) with the same shape and room volume. The houses were built in July 2005. Figure 1 shows the site plan. All had floor areas of 16 m^2 (width 4 m × height 4 m) and ceiling heights of 2.4 m. In addition, they were equipped with single glass door (width 0.9 m × height 2.2 m) on the south side and single glass window (width 1.8 m × height 2.2 m) on the north side. The wall, floor, and ceiling specifications of each experimental house are shown in Table 1. The wall composition in each house differed [16]. The walls in Type WM were a composite of mud ($t = 40$ mm) and wood ($t = 40$ mm); those in Type M were composed of mud ($t = 80$ mm); and those in Type I were insulated with glass wool ($\lambda = 0.038$ W/mK, $t = 100$ mm). Table 2 shows the calculated areal coefficient of heat loss (Q value) and the heat capacity of each experimental house, which indicate the insulation performance and thermal storage performance, respectively. Q value can be calculated by dividing the overall heat loss by floor area and the difference in temperature between outdoor and indoor. The insulation performance was highest in Type I, followed in order by Type WM and Type M. With respect to thermal storage performance, Type M was highest, followed by Type WM and Type I.

To evaluate the air tightness of each experimental house, the equivalent leakage area (C value) was measured [17]. C value (1/h) is the number of times that the whole interior volume of air is replaced per hour. It was measured by the fan pressurization method (KNS-4000; Kona Sapporo, Japan). The equivalent leakage areas for each house are shown in Table 2, which indicate that the air tightness of Type I had the highest level among three experimental houses.

Experimental period

Measurements were conducted in the experimental houses from 2005 to 2009. From 2005 to 2007, the natural indoor air temperature was measured when the air conditioner was not in use. From 2008 to 2009, the electric consumption and indoor thermal environment were measured during continuous heating and cooling. The following sections describe the measurement conditions for each case.

Measurement without air conditioning

To investigate the thermal environment naturally formed by the building itself, the outdoor air temperature, as well as the indoor air temperature when the air conditioner was not in use, was measured. The measurement period encompassed approximately 1 year from October 1, 2005, to September 30, 2006. The door and the window closed basically, while they were opened during a day two times for approximately 1 h for ventilation.

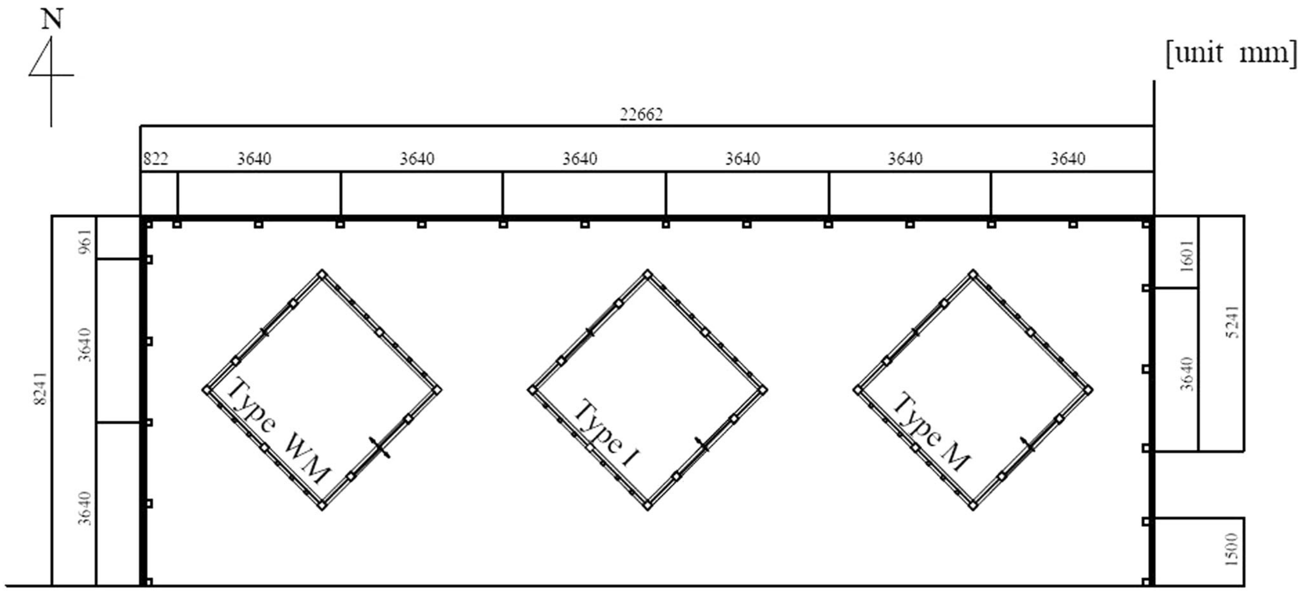

Fig. 1 Site plan

Outdoor and indoor air temperatures were measured at 15-min intervals using a temperature and humidity sensor (HIOKI E.E. CORPORATION, 3641) and a data logger (HIOKI E.E. CORPORATION, 9680). To reduce the effect of sunlight, the outdoor air temperature measurements were conducted inside an instrument shelter installed on site. Indoor air temperature measurements were conducted with temperature and humidity sensors installed in the center of each experimental house at 50 cm above the floor and in the center of the attic space.

Measurement with air conditioning

To investigate the effect of the wall composition on the electric consumption when the air conditioner was continuously in use inside the building, the indoor air temperature of the experimental house was maintained at a specific temperature. The measurement periods were summer (July 25, 2008–September 15, 2008) and winter (December 1, 2008–March 31, 2009). An air conditioner (Daikin INDUSTRIES, S28GTSS-W) was used inside the each house. The air conditioner's energy consumption efficiency was 5.77 for cooling and 6.27 for heating. The air conditioner was set at three cooling temperatures during the summer (24, 26, and 28 °C) and three heating temperatures during the winter (20, 24, and 28 °C). For each condition, air conditioning was used for 3–5 days. During measurement periods, windows were closed.

Measured parameters included outdoor air temperature, indoor air temperature, and electricity usage. Outdoor and indoor air temperatures were measured as previously described, and the electric consumption was measured at 1 h intervals using a wattmeter (Seiko Engineering, P303).

Results and discussion

Thermal environment without air conditioning

Fluctuations throughout the year

To investigate the effect of the wall composition on long-term indoor air temperature, fluctuations in indoor and outdoor air temperatures throughout the year were compared among three houses. Figure 2 shows the monthly average air temperatures during the experimental period. Throughout the year, each experimental house showed a trend of higher air temperatures recorded indoor than those recorded outdoors. The indoor air temperature fluctuation was similar in Type WM and Type I, with a maximum difference of only 0.7 °C, recorded in April 2006. On the other hand, the monthly average indoor air temperature during the winter in Type M was lower than the other types, and it was less than Type I 2.0 °C at the maximum in October, 2005.

Figure 3 shows the relationship between outdoor and indoor air temperatures in the experimental houses at 1 h intervals during the entire experimental period. Linear regression analysis of each distribution revealed that outdoor and indoor air temperature showed a strong correlative relationship in each house. In addition, the regression lines showed that indoor air temperature in each house

Table 1 Specification of each part in experimental houses

Part	Type M Material	Thickness (mm)	U value (W/m^2K) Experimented value	U value (W/m^2K) Calculated value	Heat capacity (kJ/K)	Type WM Material	Thickness (mm)	U value (W/m^2K) Experimented value	U value (W/m^2K) Calculated value	Heat capacity (kJ/K)	Type I Material	Thickness (mm)	U value (W/m^2K) Experimented value	U value (W/m^2K) Calculated value	Heat capacity (kJ/K)
Floor	Chinese quince	15	–	1.41	556	Chinese quince	15	–	1.41	556	Lumber	27	–	0.56	345
	Japanese cedar	40				Japanese cedar	40				Phenoric foam	40			
Ceiling	Japanese cedar	12	–	0.33	121	Japanese cedar	12	–	0.33	121	Plaster board	9.5	–	0.33	140
	Glass wool ($16 kg/m^3$)	100				Glass wool ($16 kg/m^3$)	100				Glass wool ($16 kg/m^3$)	100			
Wall	Mud	10	2.24	2.36	3838	Mud	10	1.78	1.57	3159	Plaster board	12	0.50	0.33	1398
	Mud	70				Japanese cedar	40				Glass wool ($16 kg/m^3$)	100			
	Japanese cedar	9				Mud	40				Siding board	12			
	Japanese cedar	10				Japanese cedar	10								

Experimented *U* value: Yamasaki [16]

occurred at a higher range than the outdoor air temperature. In detail, the indoor air temperature was higher than the outdoor air temperature in Type M 89.5 % of the time, as well as those of 95.9 and 96.8 % in Type WM and Type I, respectively. This trend correlates with the insulation performance of each experimental house. However, although the *Q* value of Type WM was similar to that of Type M than that of Type I as shown in Table 2, the trend of the indoor air temperature resembled that of Type I.

Daily fluctuations

To examine the effect of the wall composition on the short-term indoor air temperature, the indoor air temperature without air conditioning and the outdoor air temperature were compared against solar radiation levels for both seasons. Figure 4 shows the daily fluctuations of air temperature for each experimental house. Data were abstracted from periods with continuous good weather, referred to as "a large amount of solar radiation," and those with continuous rainy or cloudy weather, referred to as "a small amount of solar radiation." As shown in Fig. 4a, the winter results under the conditions of a large amount of solar radiation indicate that the daytime maximum indoor air temperature is highest in Type I, followed by Type WM and Type M. In contrast, the houses showed no temperature differences under the conditions of a small amount of solar radiation (Fig. 4b). In addition, the houses showed no differences in the minimum indoor air temperature near dawn hours (AM 6–8) regardless of amount of solar radiation. Conversely, the summer results shown in Fig. 4c and d do not indicate differences in indoor air temperature fluctuations caused by solar radiation. Type I had the highest maximum indoor air temperature, followed by Type WM and Type M, which exhibited similar levels. Similar to the winter results, no differences in the minimum indoor air temperature near dawn hours were apparent among the houses.

Increment ratio of indoor temperature

In order to examine the mitigation of external weather conditions, Fig. 5 shows the relationship between the daily mean outdoor air temperature and the daily range of outdoor (Fig. 5a) or indoor (Fig. 5b) air temperature. To simplify comparisons among the experimental houses, each data distribution is shown with a probability ellipse of 80 % [18]. In Fig. 5a, the daily range of outdoor air temperatures ($\delta\theta_{out}$) is distributed in a range below 15 °C regardless of the daily mean outdoor air temperature. On the contrary, in Fig. 5b a difference was apparent between the trends of Type M and other houses as to that of the indoor air temperature ($\delta\theta_{in}$). While $\delta\theta_{in}$ in Type M were

Table 2 Thermal performance of each experimental house

	Q value [W/m^{2}K]	Heat capacity [kJ/K]	C value [cm^2/m^2]
Type M	7.0	4515	14.6
Type WM	5.4	3836	10.8
Type I	1.5	1884	3.2

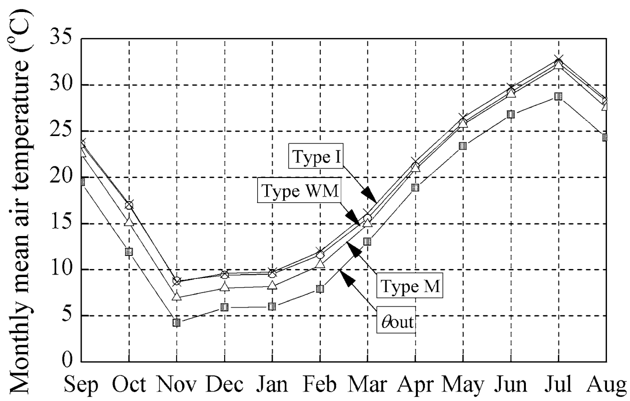

Fig. 2 Annual fluctuations of mean air temperature. Type W: house with walls of mud, Type WM: house with walls composed of wood and mud, Type I: house with walls of insulation, θ_{out}: outdoor air temperature

distributed within 10 °C, regardless of season, those in Type WM and Type I increased with decreasing the daily mean outdoor air temperature. Since the outdoor air temperature is low at night in the winter, the daily range is strongly affected by the heat acquisition and dissipation of solar radiation through windows. This influence is remarkable in the house with high-performance insulation. That is, although the indoor air temperature increased by the heat acquisition of solar radiation in day time, it decreased rapidly owing to the heat dissipation at night. Therefore, $\delta\theta_{in}$ in Type WM and Type I in the winter became higher than that in the summer and that in Type M.

Figure 6 shows the increment ratio of indoor air temperature (IR) of each experimental house. IR is defined as

$$\mathrm{IR} = \delta\theta_{in}/\delta\theta_{out} \times 100\,[\%]. \quad (1)$$

At 100 %, both of the daily ranges of outdoor and indoor air temperature are the same; values <100 % indicate that the daily range in indoor air temperature is smaller than that in the outdoor air temperature. On this basis, the effect of a building on the mitigation of external weather conditions was examined. IR was calculated each day. In addition, weighted linear regression analysis was performed to examine the relationship between the daily mean outdoor air temperature and IR. The average values for IR were 97.3 ± 45.8 % (Type WM), 74.7 ± 24.4 % (Type M), and 116.3 ± 45.8 % (Type I). According to Fig. 6a, the results of the weighted linear regression analysis in Type WM indicated that IR was 100 % when the daily mean outdoor air temperature was 15 °C. When the daily mean outdoor air temperature decreased below 15 °C, IR exceeded 100 %; when it surpassed this temperature, IR decreased below 100 %. As shown in Fig. 6c, regardless of the outdoor air temperature, IR in Type I tended to surpass 100 %. On the contrary, IR in Type M was distributed between 70 and 80 % throughout the year (Fig. 6b). In the case of Type M, it is considered that solar heat radiation through windows is easily dissipated through the walls because of the low insulation performance and high heat capacity of mud walls. Therefore, IR caused by solar radiation was suppressed during the day, and thus the daily range of indoor air temperature decreased in Type M.

Phase shift of air temperature

A phase shift of the indoor air temperature generally results in high thermal capacity of a wall. For example, Uno [12] investigated houses in Gifu and Aichi prefectures in Japan and reported that heat capacity effectively affects the phase shift of air temperature. As described in the previous section, the solar radiation heat through windows accounts for a significant portion of a building's thermal load. Then, to examine the effect of only heat transfer through walls, sunshine from the windows was blocked. As shown in Fig. 7, a phase shift between indoor and outdoor air temperatures was observed. While the outdoor air temperature reached the highest temperature at 13:45 (24.3 °C), the maximum indoor air temperatures in the experimental houses occurred at 16:00 in Type I (24.0 °C), 17:30 in Type M (21.8 °C), and at 18:00 in Type WM (22.3 °C). Compared with Type I, the highest indoor air temperature in Type M was reached later for 90 min and that in Type WM for 120 min. At dawn, the lowest outdoor air temperature (13.2 °C) occurred at 6:15, while the lowest indoor air temperatures in the houses occurred at 7:30 in Type I (18.5 °C), at 8:45 in Type M (17.8 °C), and at 9:00 in Type WM (18.5 °C). Compared with Type I, the lowest air temperature in Type M was reached later for 75 min and that in Type WM for 90 min. The response of the indoor air temperature fluctuation to the outdoor air temperature in Type I was apparently rapid, due to its small heat capacity. According to Table 2, although the heat capacity of Type M was 2.1 times that of Type WM, the

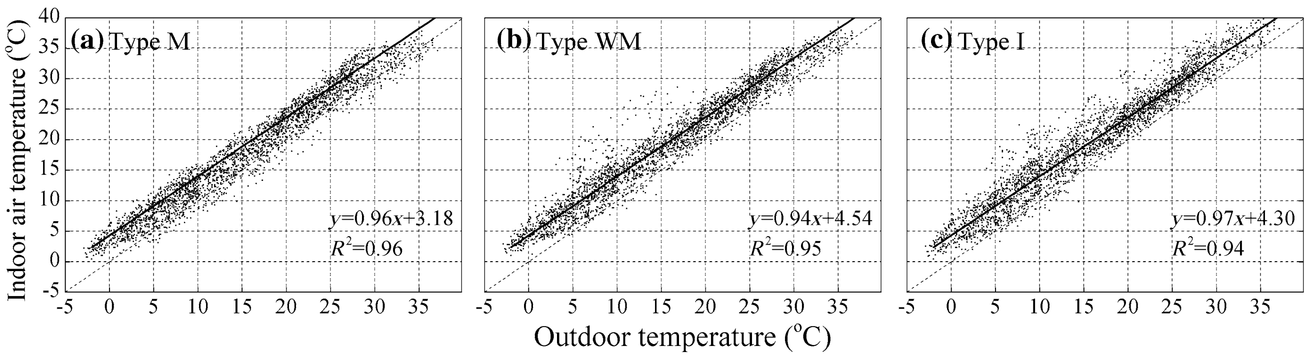

Fig. 3 Relationship between outdoor and indoor air temperature at every hour

heat loss coefficient (*Q* value) of Type M was also 1.2 times that of type WM, which indicates low insulation performance of Type M. For this reason, it is considered that the indoor air temperature in Type M was more influenced by decrease and increase in the outdoor air temperature in the evening and at night; therefore, it shifts more rapidly than that in Type WM. These results indicated thermal capacity effects on phase shift mainly, and insulation also has important role in phase shift.

Thermal environment with air conditioning

Relationship between the indoor–outdoor temperature difference and electric consumption

To investigate the effect of the wall composition on the heating and cooling loads when the air conditioner was continuously in use inside the building, the relationship between hourly air conditioner electric consumption and the indoor–outdoor air temperature difference in each experimental house was examined (Fig. 8). To render the winter and summer data on the same axis, the indoor–outdoor air temperature difference was expressed as absolute value. The periods used for analysis were September 4–15, 2008 for the summer and December 30, 2008–January 27, 2009 for the winter. For the summer and winter, 265 and 697 h of data were obtained, respectively. The ceiling and floor of each experimental house were insulated, and light from windows was blocked.

The electric consumption in the summer was highest in Type M at 226 Wh. Electric consumption for heating was larger than that for cooling because the indoor–outdoor air temperature difference in winter was larger than that in summer, the highest of which was 907 Wh in Type WM, 919 Wh in Type M, and 650 Wh in Type I.

In all of the experimental houses, there is a correlation between the indoor–outdoor air temperature difference and electric consumption, and as this temperature difference increased, electric consumption also increased. As shown in Fig. 8, the indoor–outdoor air temperature difference and electric consumption were not linear; as the indoor–outdoor air temperature difference increased, electric consumption increased exponentially. When the indoor–outdoor air temperature difference was 20 °C, the electric consumption was 328 Wh in Type WM, 395 Wh in Type M, and 293 Wh in Type I. When this indoor–outdoor air temperature difference was 30 °C, the electric consumption was 715 Wh in Type WM, 828 Wh in Type M, and 529 Wh in Type I. Thus, among the three houses, the electric consumption was highest in Type M. When the indoor–outdoor air temperature difference was small, the levels in Type WM and Type I were similar.

The relationship between the indoor–outdoor air temperature and electric consumption also can be expressed by a bi-linear relationship. Hockey-stick regression analysis [19] was used to analyze the effect of the indoor–outdoor air temperature difference on the increasing tendency of electric consumption. In this method, a predictor variable is used as the threshold to perform a convergent calculation to minimize the residual sum of the square of the two linear regressions line. As shown in Fig. 8, when the indoor–outdoor air temperature difference exceeded the threshold, the slope of regression line increased rapidly. The thresholds of each experimental house were 20.8 °C for Type WM, 20.7 °C for Type M, and 24.0 °C for Type I. Comparing the threshold for Type I with those of other experimental houses, it was 3 °C higher. That is, Type I tended to suppress the electric consumption associated with increases in the indoor–outdoor air temperature differences more effectively than the other houses. This result can be attributed to the effect of thermal capacity [16], air tightness, and the status of air conditioning equipment in the building. As the indoor–outdoor air temperature or vapor pressure difference increased, the indoor–outdoor air pressure difference also increased. In the winter, as cold air from the outside flowed inside, the thermal load became higher. Murakami [20] reported that walls with exposed timber columns tend to be less airtight than the stud wall-framed structure. Since Type I

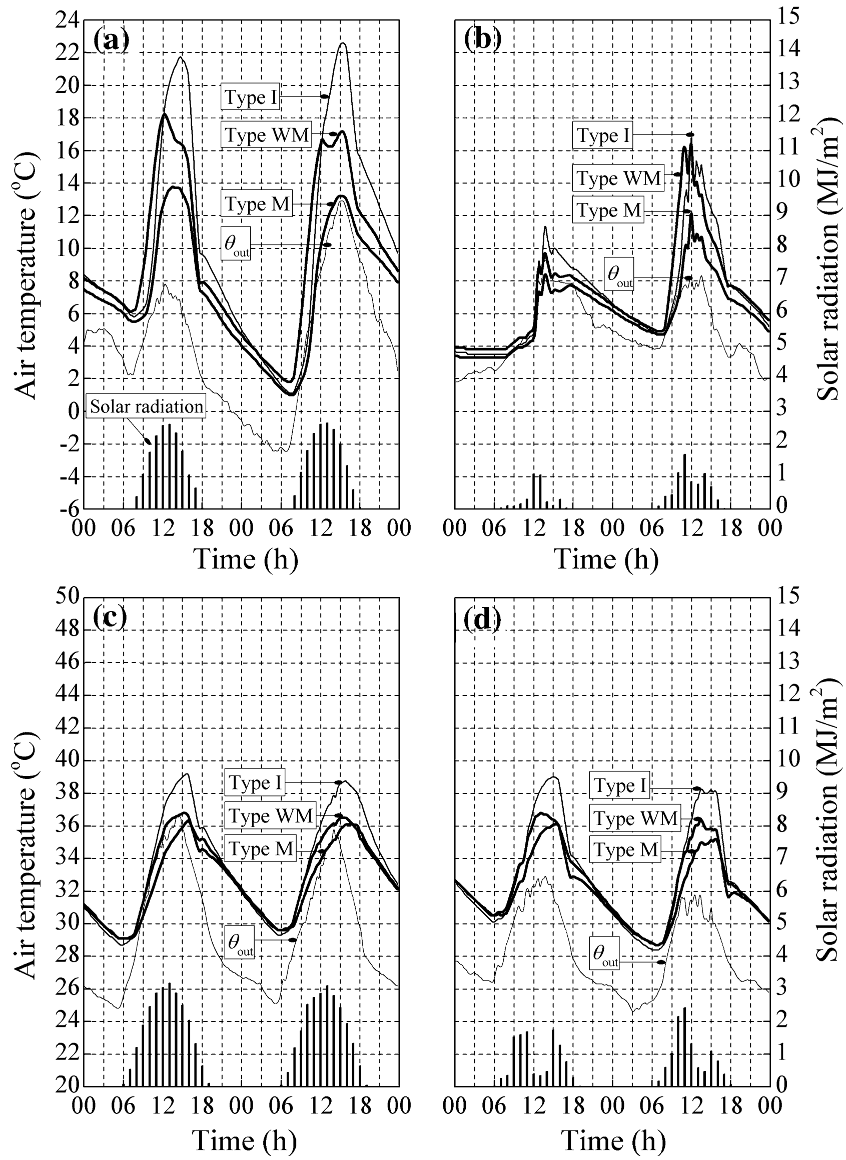

Fig. 4 Daily fluctuations of air temperature for each experimental house. **a** Large amount of solar radiation in winter (2006/2/12–2/13), **b** small amount of solar radiation in winter (2006/2/7–2/8), **c** large amount of solar radiation in summer (2006/8/5–8/6), **d** small amount of solar radiation in summer (2006/8/26–8/27)

was a stud wall-framed structure finished on both sides, its structural plywood and wallpapering increased air tightness. On the contrary, the walls in Type WM and Type M were constructed with exposed timber columns, and gaps frequently occurred between the columns and mud walls. In addition, when the indoor–outdoor air temperature exceeded 25 °C, the electric consumption increased significantly as well as other houses. The operating characteristics of the heat pump under cold conditions likely affected these results. When the outdoor air temperature is below the freezing point, frost is generated in the heat exchanger of the heat pump. To remove this frost, warm air was blown on to the heat exchanger. It is considered that this defrost operation increased electric consumption in each experimental house when the indoor–outdoor air temperature difference was significant.

Thermal storage loop: relationship between the indoor–outdoor air temperature difference and electric consumption

Figure 9 shows the relationship between the electric consumption and the indoor–outdoor air temperature difference in each experimental house of 1 day (September 17, 2009). The indoor thermal environment was controlled at a temperature of 24 °C throughout the day, and the hourly mean indoor–outdoor air temperature difference and electric consumption were plotted and connected with respect to time. At approximately 14:00, when the outdoor air temperature was highest, the indoor–outdoor air temperature difference and heating electric consumption were both less. On the contrary, these levels were the highest near dawn hours. From the viewpoint that thermal loss in the

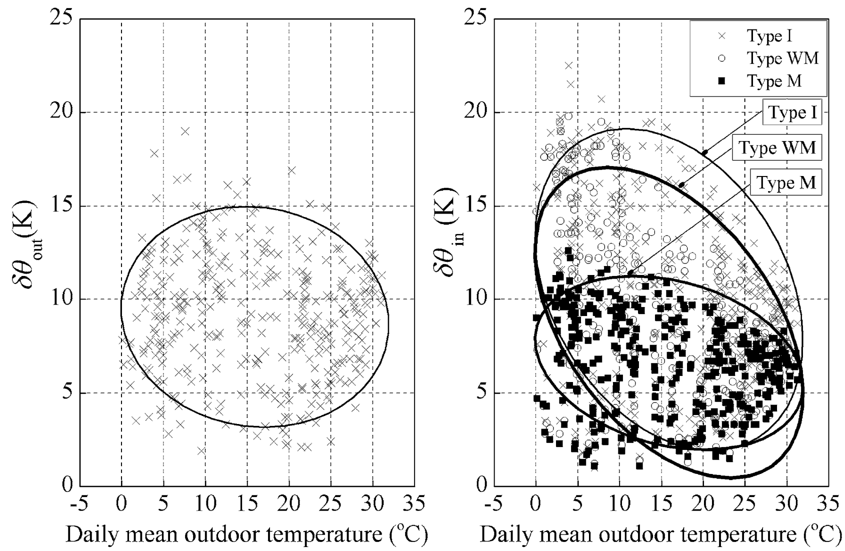

Fig. 5 Relationship between the daily mean outdoor air temperature and the daily range of air temperature. **a** The daily range of outdoor air temperature of the day ($\delta\theta_{out}$), **b** that of indoor air temperature of the day ($\delta\theta_{in}$)

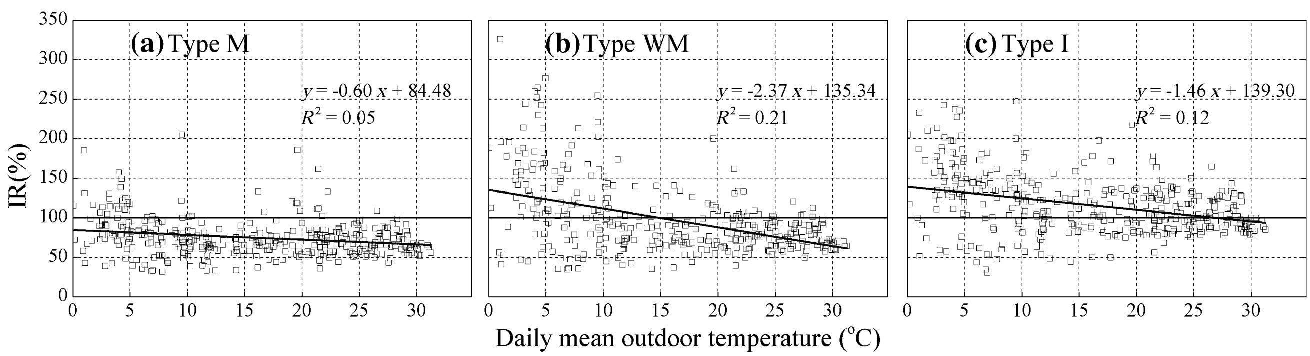

Fig. 6 Relationship between the daily mean outdoor air temperature and the increment ratio of indoor air temperature (IR). *Solid lines* express the weighted regression line

building was supplemented by air conditioning, the increase in the indoor air temperature from dawn to daytime and the decrease in that from daytime to dawn are the same. As shown in Fig. 9, however, the two processes form a loop rather than following the same line. The building's heat capacity can be considered as a cause of hysteresis. From dawn to daytime, heating energy was required to increase the indoor air temperature and the walls; however, from daytime to dawn, the heat which walls released into the room cut down electric consumption. The inner area of this loop, referred to as 'the thermal storage loop', is used in the following analysis.

Figure 10 shows the results for the thermal storage loop in the summer and winter. The average of thermal storage loop in summer was 294 ± 129 WhK (Type WM), 263 ± 117 WhK (Type M), and 184 ± 80 WhK (Type I), and that in winter was 528 ± 346 WhK (Type WM), 632 ± 311 WhK (Type M), and 342 ± 276 WhK (Type I). Since the electric consumption was lower in summer than in winter, the loop area was also smaller. Multiple comparisons using Fisher's PLSD revealed significant differences between Type M and Type I in both seasons. The trend of the thermal storage loop in Type I differed from that of the other types. The loop area was composed of the indoor–outdoor air temperature difference, electric consumption, and hysteresis. While the former two factors were determined by the building's insulation performance, air conditioning equipment, and external environment, the latter was related to the thermal storage of the building. That is, because the insulation performance was low and the thermal storage performance was high for Type M and Type WM, the electric consumption and hysteresis increased significantly, and the loop area also increased. On the contrary, the insulation performance of Type I was high, and the thermal storage performance was low. It is considered that these conditions resulted in low electric consumption and hysteresis.

In the assessment of thermal performance of buildings in Japan, they have used as index of either heat loss coefficient for insulation performance or heat capacity for thermal storage. However, the effects of the external environment on heat capacity, insulation performance, and air conditioner electric consumption were difficult to determine [21]. The assessment on the inner area of the thermal storage loop analyzed in this report can express the relationship between the outdoor and indoor thermal condition and the heat characteristics of a building, although it is relative evaluation.

Conclusions

This study reveals the influence of wooden-housing-wall structures on indoor thermal environments and assesses the energy reduction performance of housing that utilizes natural building materials. The natural indoor air temperature when the air conditioner was not in use and the amount of energy to maintain a specific indoor air temperature was measured, and then the influence of wall insulation performance and heat capacity on the indoor thermal environment was examined.

Three experimental buildings were constructed in the same region with identical parameters except for wall specifications, and simultaneous measurements were conducted for indoor and outdoor air temperatures and electric consumption. The three types of walls were composite wood and mud walls (Type WM), traditional mud walls (Type M), and insulated walls that are currently used widely (Type I). The results of this study are summarized as follows:

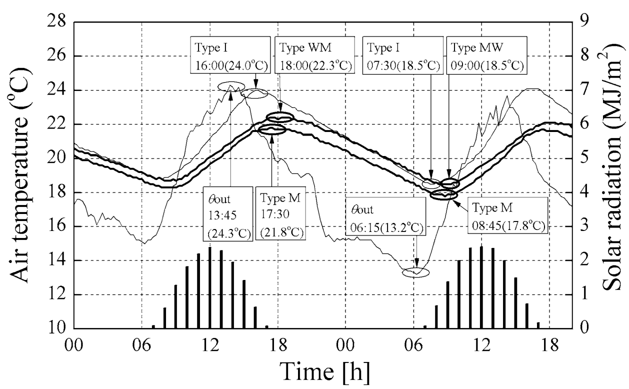

Fig. 7 Phase shift of air temperature for each experimental houses (2007/10/30–31)

1. Under the natural indoor air temperature fluctuations when the air conditioner was not in use, the monthly average indoor air temperature level and the time ratio of the indoor air temperature surpassing the outdoor air temperature were in the following order: Type I > Type WM > Type M. These results agree well with the insulation performance in each experimental house by the same magnitude. However, the trend was not proportionate; Type WM indicated a trend similar to that of Type I.
2. Examination of the increment ratio of the indoor air temperature throughout the year revealed that Type M was distributed below 100 %; Type I was distributed above 100 %; and Type WM showed a trend between Type M and Type I. In the case of Type M, the reasons of this result are that the increase in the indoor air temperature was suppressed because of low insulation performance and the indoor air temperature was equalized because of high thermal capacity
3. Examination of the phase shift of air temperature revealed a difference among three experimental houses in the appearance time of the maximum high and low temperatures. Type WM exhibited the highest phase shift of air temperature, indicating that both of the insulation performance and heat capacity affect the phase shift.
4. The indoor–outdoor air temperature differences and air conditioning electric consumption were correlative. Both variables showed a bi-linear relationship, and when the indoor–outdoor air temperature difference surpassed approximately 20 °C, the increasing tendency of electric consumption became significant.

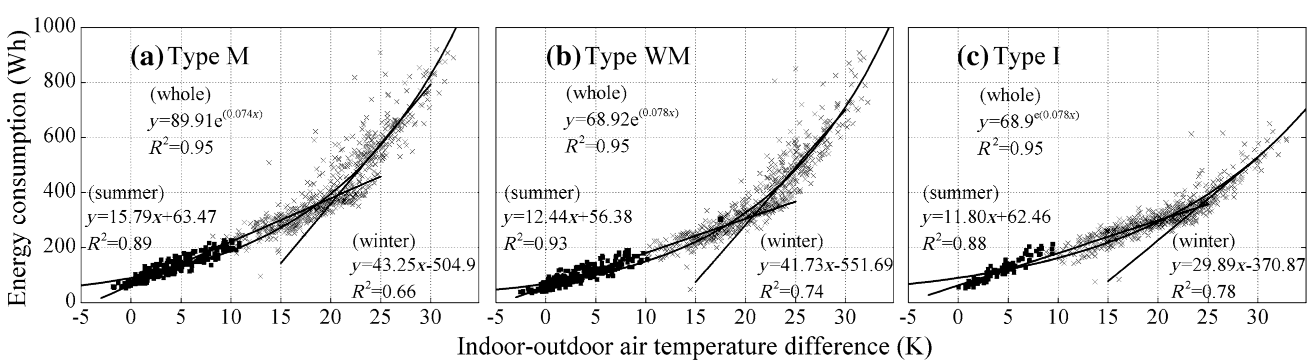

Fig. 8 Difference in season on relationship between electric consumption and indoor–outdoor air temperature difference. **a** Type M, **b** Type WM, and **c** Type I. *Filled plots* December 30, 2008–January 27, 2009 (summer), *openable plots* September 4–15, 2008 (*winter*)

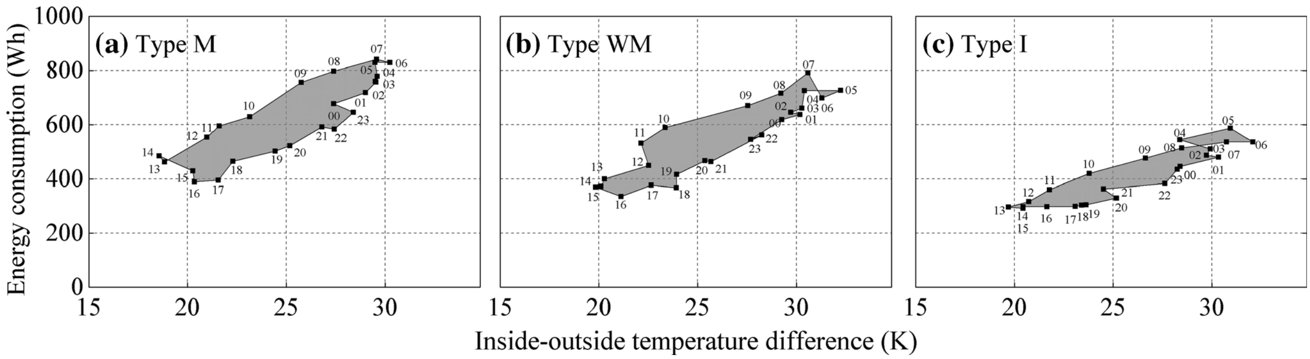

Fig. 9 Thermal storage loop (September 17, 2009). Small figures expressed time

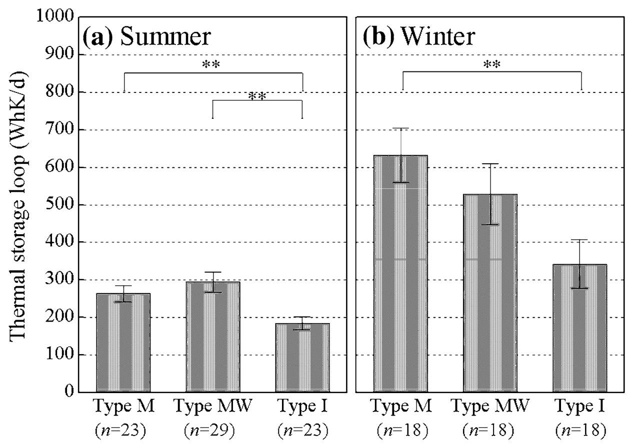

Fig. 10 Comparison of thermal storage loop among three experimental houses. Data are given as mean ± SD. **a** Summer (August 2008–September, 2008), **b** Winter (December 2008–March 2009). **Significance at 1 % significance level in Fisher's PLSD

5. The assessment on the basis that the inner area of the thermal storage loop analyzed in this report can express the relationship between the outdoor and indoor thermal condition and the heat characteristics of a building, although it is relative evaluation.

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