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Application of small-scale experimental models for thermal comfort assessment of sustainable building materials

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Abstract

Accumulation of unmanaged industrial solid waste, especially in developing countries has resulted in an increased environmental concern. In view of utilization of industrial solid waste the recycled paper mill waste (RPMW) – cement composite bricks were designed and developed. In order to investigate the environmental performance of sustainable construction materials two small scale model houses were designed and developed with waste-create (RPMW – cement) bricks and commercially available fly ash bricks as per the standards. In order to assess the thermal comfort for the considered sustainable building materials the temperature inside the model houses were monitored over the study location for the period of a year. The economic viability for the developed model houses was also analyzed. The recorded south facade exposed wall surface temperature readings for the developed small-scale model houses were used to estimate the thermal conduction of wall assembly. The detailed analysis revealed that the developed waste-create brick model house was more thermally comfortable and economical than fly ash brick model house. The better thermal performance capacity of the waste-create brick model house can drive the construction of energy efficient building so as to minimize energy consumption through the reduction of the thermal load of the built environment. The developed low cost sustainable construction material enhances the practical feasibility of the product as well.

Keywords: *Waste-create brick, Small-scale model house, Thermal comfort.*

1. Introduction

Brick is one of the important materials for the construction industry. The infrastructure such as buildings for housing and industry, and the facilities for handling water and sewage requires a large amount of construction materials. Since the large demand has been placed on building material industry, especially in the last decade owing to the increasing population, there is a mismatch between demand-supply management of these materials. Hence to meet the continually increasing demand, researchers are attempting to design and develop sustainable alternative solutions for the construction materials. Recycling of industrial wastes by incorporating them into building materials is a practical solution to the pollution problem. The use of solid waste as an alternative raw material for the development of brick is a sustainable solution.

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The raw materials used are otherwise land filled and thus, add to ever escalating cost of disposal. Attempts have been made to incorporate waste in the production of bricks [1]. In order to recover the use of raw material as a sustainable construction material A. Milani et al. investigated the incorporation of the agricultural and industrial residue of rice husk ash into the cement-stabilized rammed earth system [2]. The result showed that sandy soil, when partially replaced by maximum ash content of 7.5% and stabilized with 10% cement, proved to be a promising alternative material.

Unwanted thermal energy can accumulate in buildings and dwellings from a variety of sources, such as radiation or convection-induced heat transfer and air infiltration through walls, heat from interior appliances, equipment and occupants; and solar radiation. The use of thermal insulation and special types of building materials has increased significantly in recent years in both hot and cold climates. This is due to the increasing demand on the thermal comfort of people in residential, commercial and governmental buildings besides the ever increasing cost of energy. M. Dondi et al. [3] measured the thermal conductivity of clay bricks and investigated the correlations of the thermal performance with the compositional, physical, and micro structural features of products. K. Al-Jabri et al. [4] studied the possibility of developing concrete blocks using waste materials. The blocks were produced from the waste materials like vermiculite and polystyrene beads, which were used as lightweight aggregates with different proportions in the mix, and cement kiln dust (CKD) used as a partial replacement for cement. The thermal insulation property of the developed lightweight concrete blocks was compared. Results showed that lightweight concrete blocks manufactured from polystyrene had a lower thermal conductivity than vermiculite and ordinary concrete blocks. B. Bhattacharjee et al. [5] determined the water permeable porosities and thermal conductivity of ceramic construction materials experimentally. A model relating porosity with thermal conductivity of ceramic construction materials was proposed. The experimentally determined values of thermal conductivities reported for some bricks are then compared with those predicted through proposed model. A. Bouchair [6] studied the steady state thermal behavior of fired clay hollow bricks for enhanced external wall thermal insulation. The insulation materials injected within brick recesses during the assessment are granulated cork and expanded polystyrene. The results had shown that replacing the cork by expanded polystyrene (EPS), having a lower thermal conductivity, would not improve significantly the overall thermal resistance. E. Custodio-Garcı´a et al. [7] Performed mechanical and thermally controlled measurements of walls made using modern construction block material and the traditional red fired clay brick material. It was observed that the ancient tradition of using fired clay bricks, for the weather conditions in central Tabasco represents an excellent alternative in cost and energy savings for construction. M. Ozel [8] determined the thermal performance of building walls constructed of concrete, briquette, brick and autoclaved aerated concrete (AAC) for uninsulated and insulated wall structures. A. Chel et al. [9] had carried out the case study of thermal performance and embodied energy analysis of a passive house. R. Ralegaonkar and R. Gupta [10] constructed and analyzed small-scale experimental models of actual construction material with insulating material for varying static sunshades. Lertsatitthanakorn et al. [11] reported on the comparative performance of a rice husk ash (RHA) based sand–cement block room with that of a standard commercial clay brick room. The RHA-cement block reduces solar heat gain in buildings and the comparisons included an evaluation of room temperature, solar conduction heat transfer and economics. M. Khorami and J. Sobhani [12] experimentally investigated the applicability of asbestos replacement with three types of agricultural waste fibers, including bagasse, wheat and eucalyptus fibers. The results attested the applicability of utilized waste agricultural fibers in production of cement composite boards by improving the flexural and energy absorption characteristics, more or less, depending on the type of fibers. A. Allahverdi and E. Najafi Kani [13] investigated geopolymerization of construction waste materials with different alkali-activators based on combinations of Na2SiO3 and NaOH. A number of systems were designed and prepared with water-to-dry binder ratio, silica modulus, and sodium oxide concentration was adjusted at different levels and setting time and 28-day compressive strength was studied. The results obtained reveal that construction wastes can be activated using a proportioned mixture of Na2SiO3 and NaOH resulting in the formation of a geopolymer cement system exhibiting suitable workability and acceptable setting time and compressive strength.

The need for solid waste management and sustainable insulating material are becoming important issues. The present paper aims at comparing the performance of recycled paper pulp- cement bricks to commercially available bricks with reference to the thermal performance of the model house. In the present study locally available fly ash bricks were used as a conventional brick.

2. Materials and Methods

Recycle paper mill waste (RPMW) was obtained from M/s Madhydesh Paper mill, Nagpur, India. The characterization of RPMW was done [14]. The RPMW thus obtained was used for making building blocks by mixing with Portland cement in different weight proportions. Hand operated hydraulic press was used to make bricks of dimensions 230 X 105 X 80 mm^3. The mixes of RPMW and cement with different compositions were prepared. RPMW weight percentages in the composition mix were varied from 80% - 95%. In the mixing process of samples, RPMW and cement contents were placed in a mixer and mixed for 2 min. In order to obtain more homogeneous mixes, the water was sprayed by air pump onto the mixes and mixing was conducted for another 5 min. Afterward, the fresh mixes were fed into the steel molds. The mix was pressed in the mold till its initial moisture was removed. The brick was taken out and kept for solar drying till its moisture further reduces by another 15 ± 3%. The semi-dried brick was further pressed till its moisture content was reduced by 10 ± 2% and then kept for final sun drying. The methodology followed for manufacturing waste create brick is shown in Fig.1. The mechanical properties of the RPMW-cement bricks (Table 1) were tested and the same was presented [14]. Commercially available fly ash bricks were used having ingredients of ordinary Portland cement, thermal station fly ash, crushed sand/stone dust and admixtures. The physico-mechanical properties of fly ash bricks used are presented in Table 1.

Table 1 Properties of brick (IS 3495: 1992)

Type of Brick	Compressive Strength (MPa)	Water Absorption (by weight) (%)	Density (kg/m^3)	Thermal conductivity W/mk	Efflorescence
Fly Ash Brick	3.12	14.64	1750	1.05	NIL
Waste-create brick	9.91	100	670	0.3	NIL

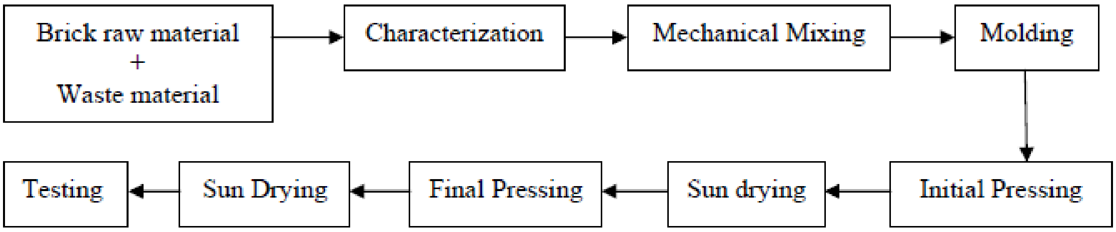

Fig. 1 Methodology followed for manufacturing RPMW brick

2.1. Development of model house

Two different model houses facing towards north were built by the developed waste-create bricks (model M-1) and commercially available fly ash bricks (model M-2). The small scale experimental model houses were built with 1m height and 1m X 1m in the plan. One door of size 0.3m X 0.7m on north side wall panel and one window each of size 0.3m X 0.3m on remaining three side wall panels was provided in case of both model houses. The total area of opening were 0.27 m^2 excluding area of the door as per the requirement of SP7:2005 (National building code of India) [15]. The wall thickness for model houses M-1 and M-2 was kept 125 mm. The isometric sketch of model house is shown in Fig. 2. The built model house is represented in Fig. 3.

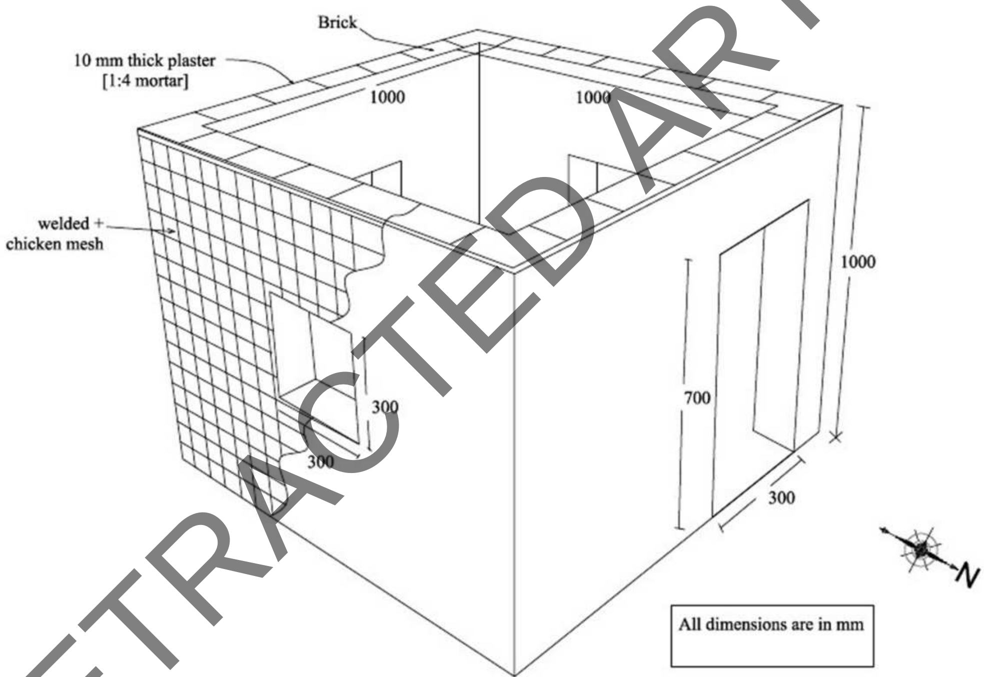

Fig. 2 Isometric sketch of Model house

Model M-1 Model M-2

Fig. 3 Model house of waste-create bricks and conventional bricks

As the water absorption for RPMW-cement brick was significantly higher, the ferrocement technique with 1:4 mortar mix was used to build a model house M-1 with 2 mm air gap on both sides of wall panel to avoid the direct contact of moisture on the surface of RPMW-cement brick wall. Ferrocement is a versatile form of reinforced concrete made of wire mesh, sand, water, and cement, which possesses unique qualities of strength and serviceability. It can be constructed with a minimum of skilled labor and utilizes readily available materials [16]. The model house M-2 was developed by using commercially available fly ash bricks with 1:4 mortar mix. The corrugated green fibre sheet of 5 mm thickness was provided as a roof material for each model house.

3. Test Methods

The model houses were built in shadow free area on the terrace of Civil Engineering Department, Visvesvaraya National Institute of Technology campus, Nagpur, in the central India. In this study, the thermal behavior of both the model houses was investigated, in order to assess its response to the local weather conditions of the city of Nagpur, in the central India, where the model houses were built. The climate variable (ambient temperature and indoor temperature) at the installation site was recorded in the months of October to June for every 1 hour via a data logger sensor (Model Digi Log Series, 8/16 Channel Universal Digital Process Data Recorder [17]) installed in the center and at the desk level (0.3 m from the floor) of the model houses [18]. In this paper the maximum, minimum, average indoor and ambient temperature of model houses was presented from October 2011 to June 2012 (Fig. 4, Fig.5 and Fig.6). The seasonal classification for the location where the experiment was carried out is presented in Table 2 [19]. The thermal comfort is the predominant parameter in the city of Nagpur and hence the thermal behavior of both the model houses was analyzed excluding the rainy season. During the rainy season, due to the unavailability of clear skies, the ambient temperature recordings were found well within the comfort range and excluded from the thermal performance analysis.

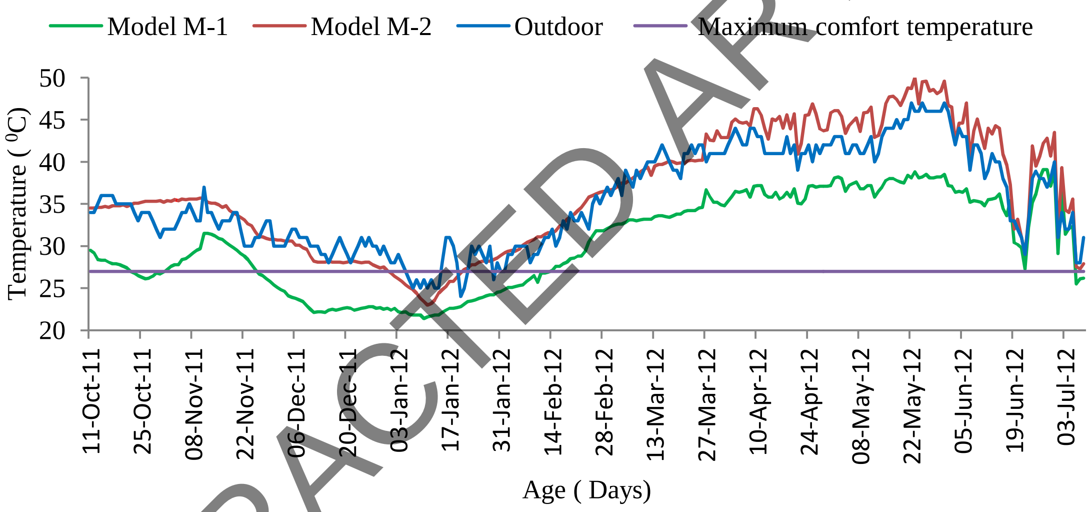

Fig. 4 Variation of maximum indoor temperature of model houses

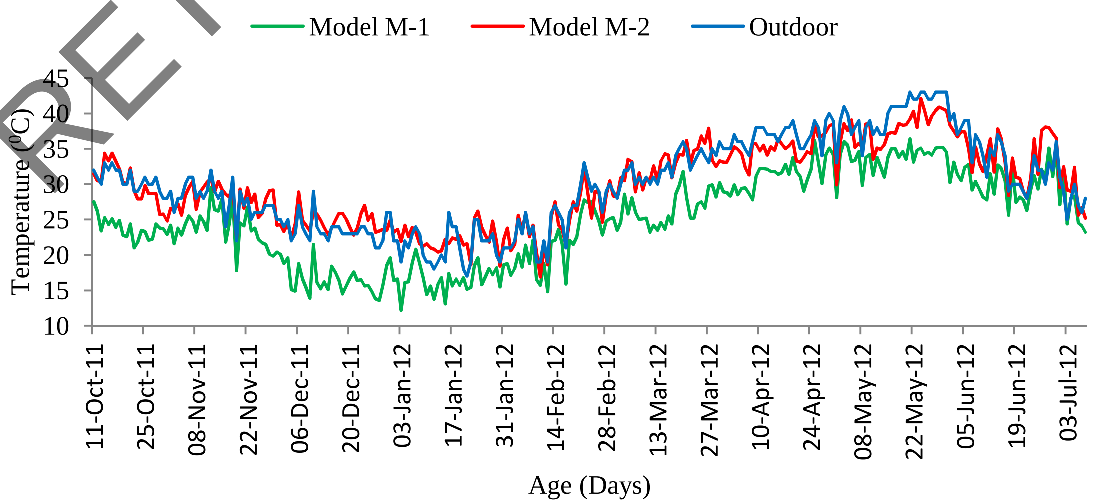

Fig. 5 Variation of minimum indoor temperature of model houses

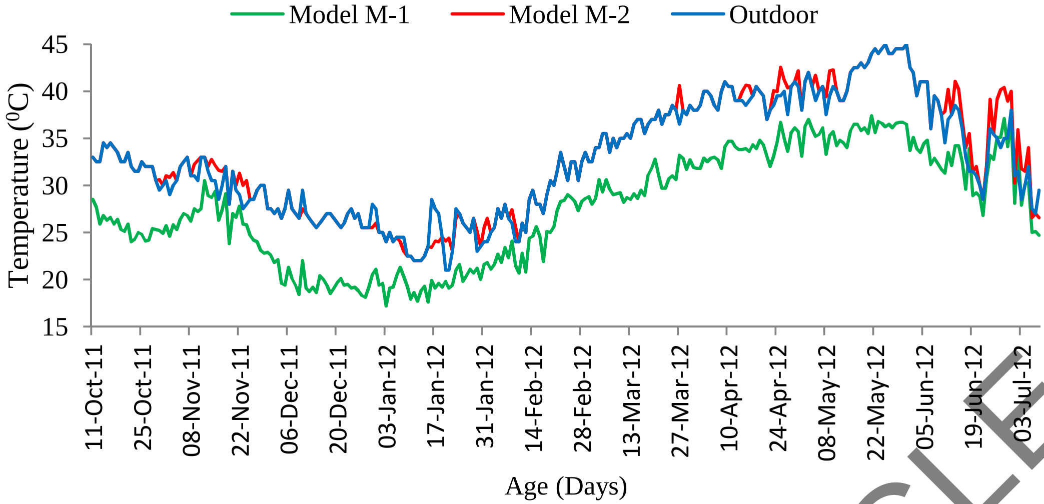

Fig. 6 Variation of average indoor temperature of model houses

Table 2 Seasonal classification

Seasonal classification	Months	Maximum Temperature (^{0}C)	Minimum Temperature (^{0}C)	Average Temperature (^{0}C)	Relative Humidity (%)
Moderate Winter	October	37	16	26.5	57.5
	November	43	14	28.5	50.5
Winter	December	33	10	21.5	52.5
	January	32	7	19.5	60
	February	39	9	24	42.5
Summer	March	42	15	28.5	30
	April	44	22	33	36
	May	47	23	35	30
	June	46	22	34	53
Rainy	July	35	22	28.5	75
	August	34	22	28	74
	September	34	21	27.5	70

As perspiration evaporation depends on the pressure gradient between skin surface (saturated vapour pressure) and ambient air (vapour partial pressure) the humidity of the air has an impact on the thermal comfort. The higher the relative humidity, the lower the heat transfers by perspiration evaporation. If the ambient air has a high temperature, in addition to high humidity, it will be sensed as uncomfortable. The comfort range of indoor humidity values is in between 30% to 70% [20]. In the tropical region where the present study was carried out, the relative humidity was in the comfort range and hence excluded.

4. Results and Discussion

4.1. Thermal performance of model house

The use of thermal insulation materials, particularly wall materials, is the major issue in today's construction industry aiming to save energy. The solution of the problem of energy saving, in the construction sector, could be achieved by prudently chosen materials, as is demonstrated in the conductance of the waste-create bricks and conventional brick model houses of this study. In accordance with the handbook on functional requirements of buildings (other than industrial building) SP 41 [21], the comfort range of the temperature is 18 ^{0}C to 27 ^{0}C.

In this study, by using Simpson's rule for integration, areas under the temperature curves were calculated. It is evident from Fig. 4 that the model house M-1was determined to be 20% cooler than model house M-2. Based on the recorded data for temperature over the experimental duration it is estimated that around 26% and 5% area is in the comfort range for M-1 and M-2 model house respectively. The maximum temperature of 39.1^{0}C and 49.5^{0}C were observed in summer and 21^{0}C and 23^{0}C in winter for the model house M-1 and M-2 respectively. The temperature in model house M-1 was in an average 4^{0}C less than that of the ambient temperature whereas the temperature in the model house M-2 was almost similar to ambient temperature over the recorded time duration (Fig. 4, Fig.5 and Fig.6). The recorded temperature of model house M-1 was on an average 3.5^{0}C less than the temperature obtained in case of model house M-2 as the model house M-1 was made from waste-create bricks, which was much more porous and fibrous material than fly ash, and the pores, as they contain air, conduct less heat, thus making the waste-create material less thermally conductive than fly ash. The Thermal conductivity of waste create brick was 72% less than that of fly ash brick which in turn increased the thermal resistance capacity of waste create brick by 46% to that of fly ash brick. Cost analysis of the waste-create brick was evaluated and compared with the cost of the commercial brick. The cost of the waste-create brick is almost 50% less than that of conventional bricks available in central India. It is also observed that the cost of construction per square meter by using waste-create brick is 35% less than the construction cost of the structure by using conventional bricks.

The walls of both the model houses were exposed to solar radiation, and recordings of the variations in the outside and inside surfaces were made. The measurements were recorded during the daytime on 11th October 2011 and it was observed that the maximum surface temperature was on the south side wall for both the model houses. A comparison of the outside and inside surface temperatures of the south side wall of both the model houses is shown in Fig. 7. It was found the inside surface temperature of the south side wall of the model house M-2 was higher than the inside surface temperature of the south side wall in the model house M-1. This was attributable to the waste-create brick having a lower thermal conductivity than the commercial fly ash brick.

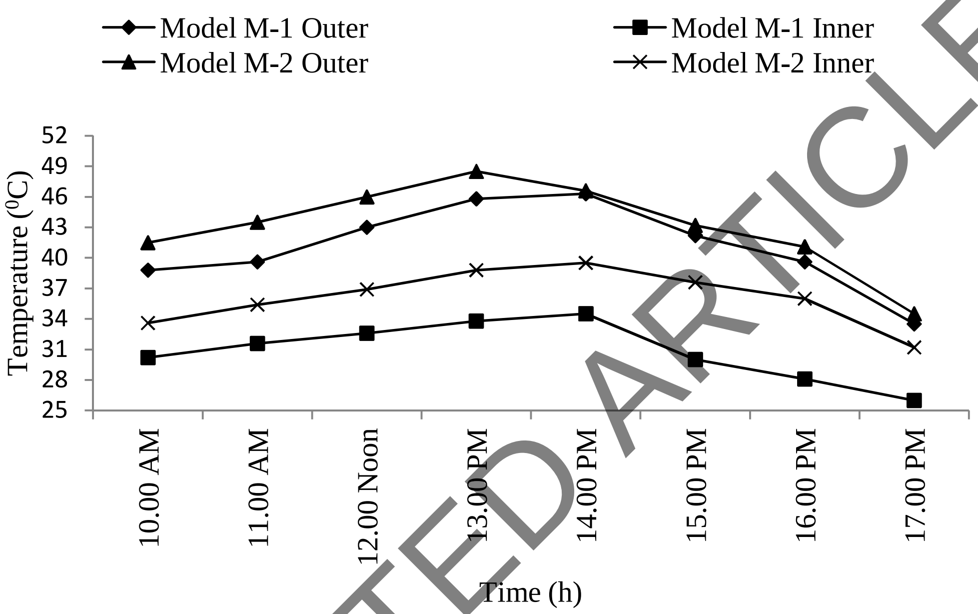

Fig. 7 Variations of the outside and inside surface temperatures of south side wall for the waste-create brick model house and the fly ash brick model house (11th October 2011)

Consequently, solar conduction heat transfer from outside to inside surfaces of the waste-create brick wall is lower than the fly ash brick wall. The conduction heat transfer, thermal resistance and thermal transmittance [22] are then given by the following expressions.

$$Q_{cond} = kA\frac{T_1 - T_2}{L} \quad (1)$$

$$R_T = {l_{(1-n)}}/{k_{(1-n)}} \quad (2)$$

$$U = {1}/{R_T} \quad (3)$$

where Q_{cond} is the conduction heat transfer rate,

k is the thermal conductivity,

A is the wall area,

T_1 and T_2 are the temperature of outside and inside walls, respectively,

L is the thickness of the wall,

R_T is the total thermal resistance

l is the thickness of the various parameters in the assembly

U is the thermal transmittance

By applying eq. (1), (2) and (3) to the temperature differences during the day, the conduction heat transfer rate, thermal resistance and thermal transmittance of south side walls for both model houses were calculated. The calculations shows the south side wall of model M-2 giving a maximum higher conductive heat transfer than that of the waste-create brick wall by about 33.8 W as shown in Fig. 8.

The thermal resistance and thermal transmittance of waste-create brick wall and fly ash brick wall is represented in Table 3. The thermal resistance of the south side wall of model M-1 is 46% higher than the thermal resistance of the south side wall of model M-2. The higher thermal resistance capacity of the waste-create brick wall can drive the construction of energy efficient building so as to minimize energy consumption through the reduction of the 20% thermal load of the built environment.

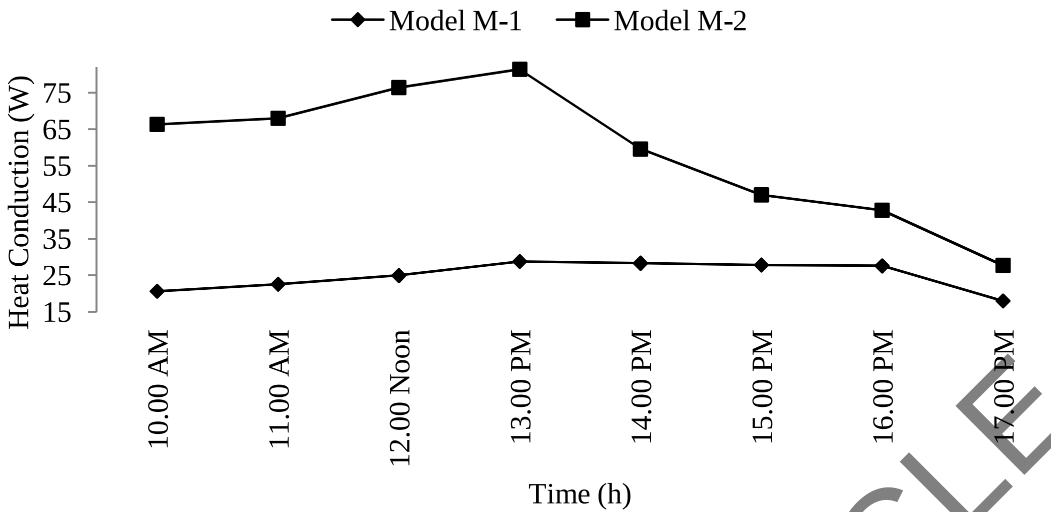

Fig. 8 Comparison of conduction heat transfer between the waste-create brick wall and the fly ash brick walls

Table 3 Thermal resistance and thermal transmittance

Wall type	Total thermal resistance (R_T) (m^2k/w)	Thermal transmittance ($U = 1/R_T$) (w/m^2k)
Waste-create brick wall	0.534	1.87
Fly ash brick wall	0.284	3.52

5. Conclusion

The small-scale modeling technique had been effectively applied for thermal comfort assessment of the studied sustainable building materials. Waste-create brick showed lower thermal conductivity and higher physical stability with respect to fly ash brick. The developed waste-create brick model house was found to be more thermally comfortable and economical than fly ash brick model house. The good thermal performance capacity of the waste-create brick model house can drive the construction of energy efficient building so as to minimize energy consumption through the reduction of the thermal load of the built environment.

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