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An empirical study on the thermal behavior of rice husk in eco-friendly brick for external walls of buildings

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Natural materials; Waste; Thermal comfort; Thermal performance; External envelope

Abstract

This study aims to analyze the behavior of natural and waste materials when applied to building brick for walls of residential buildings on the indoor temperatures and thermal comfort of residential buildings. In this study, small-scale residential rooms were built during a period of hot weather in Egypt. A comparison between models and a reference model using the traditional burned clay brick was conducted. The results indicate that the mud-brick leads to enhanced thermal behavior by 25% within comfort limits and the surface temperature difference could reach 4.3 K, whereas the compacted bricks achieve 15%, and the temperature difference was found to be 4 K; compared with the traditional fired bricks with 2.1 K surface temperature difference. Scanning electron microscopy showed large holes and cavities in the mud and compacted bricks. Whereas, in the fired clay brick small holes were observed; this difference in structure is hypothesized to lead to the difference in the thermal behavior of the bricks. The thermal conductivity(U), of the unfired mud-brick, was 0.27 W/m.K, U =0.32 W/m.K for compacted soil brick while burned bricks U=0.6 W/m.K. Based on the results, the combinations of rice husk as a waste material, mud, and compacted soil for brick lead to reducing cooling needs and sustainable building materials for new buildings in the hot and dry climate in Egypt.

1. Introduction

The construction industry represents one of the most energy-consuming sectors and consumes the largest quantity of natural materials. The construction sector consumes nearly 40% of the total energy produced globally [1,2] and leads to one-third of the global carbon dioxide

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emissions. In the absence of an increase in the use of new and renewable energy sources [3], it is expected that global energy consumption will double by 2050. The building materials sector contributes about 39% of global greenhouse gas emissions, and the rate of carbon dioxide emissions from the construction sector has increased by about 23% from 2009 to 2020; annually, the sector produces 40% of waste materials [4,5]. The concept of sustainable development has become increasingly important; this concept has the clear aim of preserving natural resources in all sectors and economic activities[6] including all stages of the construction sector, which includes design, implementation, operation, selection of structural systems, and buildings, reuse, recycling, and demolition. Several studies have highlighted the need to achieve energy efficiency at every stage of the life cycle of a building [٦]. Many experiments have studied the possibility of using new materials and technologies in future constructions; such work has investigated energy and resource efficiency, water conservation, improving indoor air quality, and reducing costs [7]. Studies have indicated that the use of natural building materials and building materials derived from recycling processes can save about 50% of energy during the life cycle of a building [8]. Such schemes can reduce the operational energy consumption of residential buildings by 44.8% and greenhouse gas emissions by 56.4% over the lifetime of a building [9]. Research indicates that recycling or incorporating waste into building materials can reduce the heat gain of a building and reduce the temperatures within residential spaces by 25% and 21%, respectively, and thus such actions would reduce energy consumption [10]. Studies indicate that sustainable natural building materials reduce the consumption of natural materials and the environmental impact caused by the extraction, transportation, and processing of materials. Some studies have indicated that the use of natural materials reduces the greenhouse gases emitted from buildings by 56.6% during the life of the building [11].experimental studies investigated the use of natural and waste materials in building construction such as agricultural waste [12,13,14,15,16], construction waste [17,18,19] Studies have proven that the heat gain by 21% and reduce indoor temperatures of residential spaces by 25% [11] which leads to improved thermal conditions, and thus these materials reduce energy consumption.

Also, Studies have indicated that the building envelope is the largest contributing factor to thermal comfort within residential spaces; as such, many different types of bricks in the external walls cement bricks could lead to lower electricity consumption by 12.8% [20], gypsum-covered clay panels have been found to reduce temperatures 2.5 K compared traditional brick walls [21]. Clay bricks can increase the heat capacity of the external walls [22,23]; compacted bricks including waste produced from the excavation, can reduce the operational energy consumption of a building by 26% compared to traditional clay bricks [24].

Whereas, studies indicate that half of the energy consumed in construction is lost through the external walls, which necessitates the completion of research in the field of the building envelope, especially the building bricks, whose demand is increasing rapidly with the increase in demand for housing units in developing countries. In previous studies on bricks, it was noted that adding waste to the bricks contributes to improving the thermal properties, in addition to contributing to reducing waste materials and recycling it, which contributes to reducing the carbon footprint. For example, many researchers have added agricultural waste such as natural fibers to help increase the pores of the bricks and reduce thermal conductivity. Some researchers have also added agricultural wastes such as wheat ash [25], rice straw could contribute to increasing the apparent porosity and reducing the thermal conductivity by 31%, and sugarcane ash contributed to a reduction in thermal conductivity by 29% [26]. The researchers also found the incorporation of rice husk ash, and polystyrene foam for compacted earth bricks could improve the properties of dry density and thermal conductivity and improves indoor air quality [27]. From industrial wastes, some studies applied coal fly ash [28], fly ash [29,30], which led to a reduction in the weight of the bricks. Carbonated sludge, led to an increase in the apparent porosity of the samples by 40% and contributed to reducing the thermal conductivity from 0.79 W/m.K to 0.26 W/m.K. Adding glass waste to brick contributed to reducing thermal conductivity to 0.52 W.m.K. Also, when using marble sludge, could lead to product lightweight bricks with an increase in the apparent porosity of the bricks, which contributed to an improvement in the decrease in thermal conductivity by 16% [31], and reduced thermal conductivity from 0.97 to 0.40 W/mK [32].

The importance of this study lies in applying agricultural waste, including rice husks, in sustainable, environmentally bricks with low thermal properties that allow a reduction in thermal conductivity in a hot, dry climate in Egypt. The burnet rise ash is considered a massive environmental and health impact of open burning [33,34] with an amount of 3.1 million tons/year and responsible for CO2 emissions of (1.2 M ton CO2/year) [35] according to an environmental report in Egypt [36]. İn addition, the rice husk has mechanical and thermal properties when added to brick [37,38,39,40]. Also, there is a lake of research available on the effects of the southern walls on thermal behavior, which are more exposed to solar heat gain [41]. Most of the existing literature focuses on treating traditional clay brick walls with insulating materials and using shading systems for southern walls to improve thermal comfort within residential spaces without using natural building materials and waste, which can be suitable for the hot, dry climate in Egypt.

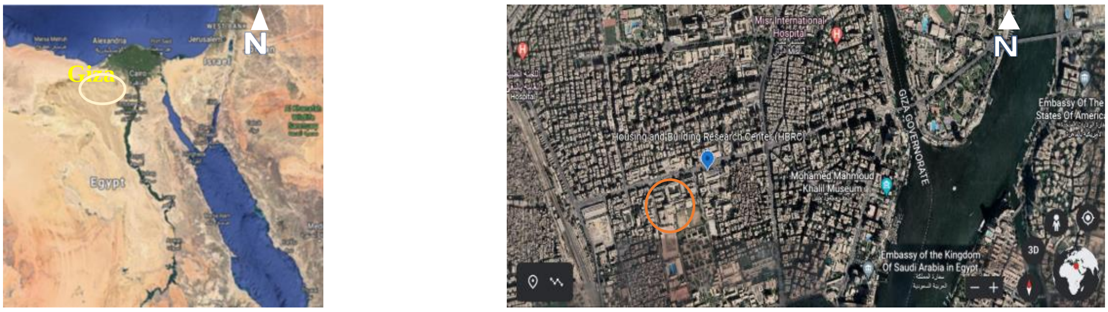
2. Methodology

A comfortable thermal environment is important to satisfy the users of the residential space, and it is necessary to undertake physical activity efficiently and achieve a feeling of satisfaction, so we have to reduce the heat gain resulting from external walls as they are one of the elements of the outer envelope responsible absorbing heat solar radiation. This work aims to reduce the heat absorption into residential spaces by using natural materials and waste products for external south-facing walls. The main objective of this research is to promote natural and waste products, such as rice straw and excavation waste, in the production of building materials. Research has demonstrated the importance of using models to predict both the indoor temperature and thermal comfort of residential spaces. Small-scaled models contribute to saving materials, time, and cost [42]. Small-scale model rooms were built on a roof in Giza city; this location allowed the air to flow without any obstacles and did not cast shadows on the models. The internal and external temperatures of the model structures were measured and recorded. The internal and external conditions of the models were measured via the placement of the internal thermometer in the middle of the model. The data was recorded over four consecutive days [43,44] during the hot period in July and August in Egypt; the models were exposed to natural ventilation by opening the door and window from 8.00 PM. to 8.00 AM. The models were located at the same level and the models were orientated in the south-north direction under direct sunlight and wind during the measurement period. Night ventilation was used in this experiment as it represents a low-cost, passive cooling method that reduces the cooling in residential spaces, and reduces indoor air temperature [45,46,47]. The thermal comfort of the model buildings was evaluated based on measurements of the internal and external temperatures over the period July 18–22, 2019, and August 11–15, 2019. These dates were selected to study thermal comfort during high outdoor temperatures. These experiments were conducted using data recording devices measuring the outdoor temperature, humidity, and air velocity; thermal comfort assessments were based on ASHRAE Standard No. 55, 2010.

The experiment was performed using models R0, R1, and R2. R0 was used as a reference model, the first test case model is referred to as R1, and the second test case model is referred to as R2; different strategies were adopted in building materials for the southern walls of the model cases. The southern walls were chosen as they are the most exposed to solar radiation [27]. Also, the study focused on one element (the southern wall) to clarify and measure changes to one element of external walls that could be measured and applied to all external walls. For the R0 model, the traditional burned clay bricks were used (in the Egyptian market). for the R1 model, adobe bricks were used with an addition of rice waste (15% by weight). rice husk which represents 2.5 million tons annually in Egypt, according to the Ministry of Environment's report for the year 2020. In the R2 model, compacted clay was used with rice husk waste (15% by weight). An experiment was conducted to clarify the effect of these two materials during the hot season on thermal comfort within residential spaces.

2.1. Experimental procedure

A) Experiment location and climate data analysis. The experiment was conducted on the roofs of administrative buildings in the Housing and Building Research Center in Giza at a height of 25 m. The surrounding buildings have similar heights and thus do not block wind flow or direct sunlight on the models. The city of Giza is located at 29°58′34″N 31°7′58″E, has an area of about 62.5615 km^2 [48], and is situated at an altitude of 23 m above sea level. The average annual temperature is 21.2°C and the average annual rainfall is about 17 mm, according to the classification (BWh) [49]. The highest average temperature during the day in Giza is about 42.5°C and 23.1°C during the night and the relative humidity ranges between 39% in May and 54% in August [50]; the prevailing winds are northeasterly/northerly. The largest amount of precipitation is about 0.2 mm in January, February, and December followed by March, April, and May with 0.15 mm. In general, the city of Giza is characterized by the scarcity of rain [51]. Figure 1a. shows the location of Giza city on a map of Egypt, and Figure 1b. shows the satellite image of the experiment location.



a) The experiment site on Egypt map. b) Satellite image of the experiment location (HBRC).

Fig.1. Location of the experiment location.

B) Experimental models. The model residential rooms were of dimensions 1.4 × 1.4 × 1.4 m, the small-scaled dimensions have been used in many experiments to evaluate the thermal performance of the outer envelope of a building subject to natural ventilation [52,53,54]. The ceiling of the models was constructed to have a resistance value equal to that of traditional residential buildings. The thermal transmissivity value of the walls was 1.53 W/m2K and the total thermal transmissivity value of the ceiling was 1.78 W/m2K, and the thermal transmissivity value of the floor was 1.79 W/m2K according to the calculations of the thermal transition of all elements of the models [55].

- Model R0 (reference case): The walls were built with a thickness of 12 × 6 × 25 cm. All the walls were built from fired clay bricks using an external and internal cement plaster layer with a thickness of 1.0 cm; thus, the total wall thickness was 8 cm. The model had a roof with a resistance value equal to the roof of the traditional residential building. The traditional building model was chosen according to the evaluation of the constructions typical of the housing in Egypt; this type of construction represents 60% of the total housing in Egypt **[**56**]**.
- Model R1 The first case model: walls of the R1 model were built to those used in the reference model except for the southern wall, which was built of mud bricks with additional material taken from rice husks (consisting of mud, sand, cement, and rice husks); the brick dimensions is of 12 × 6 × 25 cm. All model walls, with external and internal cement plaster layer of thickness of 1.0 cm.
- Model R2 (The second case model R2): The walls of the R2 model were built as shown in the reference model R0 except for the southern wall. The south-facing wall was built of compacted bricks (composed of clay, sand, and cement) with dimensions 12 × 6 × 25 cm with a layer of external and internal cement plaster with a thickness of 1.0 cm [46,57].

B) Experimental procedure. The experiment was conducted as follows**:** 1) The bricks for use in the southern wall of the model R1 were produced at the experiment site according to methods used in previous studies [58,59,60,61]. The compacted clay bricks for the model R2 were produced at the experiment site according to previous studies [62] (as shown in Figure 2b). 2) The reference model (R0) and the first test model (R1) were built, as shown in Figure 3. 3) The measurements of the internal and external temperatures of the models R0 and R1 were carried out during the hot period of July 18–22, 2019. 4) The second test model (R2) was built by removing the southern wall of the first case model (R1) (Figure 2b) and then building the southern wall of compacted bricks (see Figure 2c). The measurements on the models were then carried out over the hot period of August 15–11, 2019; the models were subject to natural ventilation from 8 pm to 8 am**.**


a) Burnt clay bricks b) Mud bricks c) Compacted bricks

Fig.2. The bricks used in the experiment models a) Burnt clay bricks, b) Mud bricks (mud, rice husks, sand, cement), c) Compacted bricks (clay, sand, cement)


a) the reference room R0 b) The south wall R1 c) The south wall of R2

Fig.3. The experimental room models (R0, R1, and R2)

C) Experimental measurements. Figure 4 shows field measurements for the room the models: a) refers to the location of the temperature sensor on the external south-facing wall, b) shows the location of the internal temperature measuring device (OPUS10), and c) shows the Thermo cable wires that connect the thermal sensors to the multichannel data logger (GRAPHTEC).

Figure 5. Shows the laboratory measurement devices used on the brick samples: a) shows the thermal conductivity measurement device, b) shows the thermal sample drying device and c) refers to the electronic sample surface scanning device (MSC).

a) The location of the thermal sensor on wall b) The inner temperature measuring evice(OPUS10) c) Multi-channel data logger recorder (GRAPHTEC)

Fig.4. The field measurements for room models.

a) The thermal conductivity measurement. b) The thermal dryer samples. c) Scanning electron microscope (SEM).

Fig.5. The laboratory measurements devices

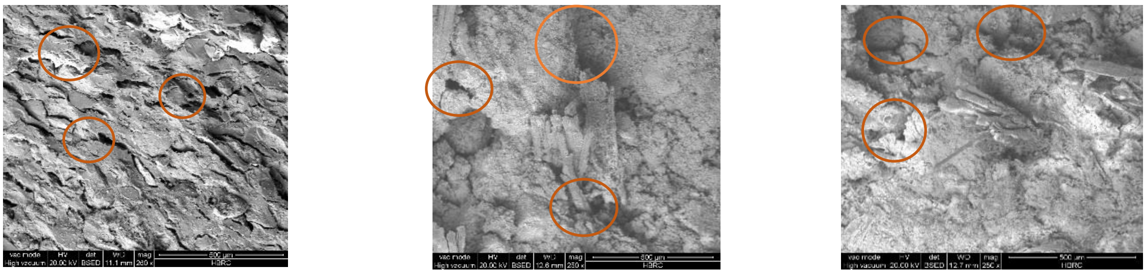
3. Results and discussion

The thermal conductivity of the clay bricks (R0), mud bricks (R1), and compacted bricks (R2) used in the south-facing wall of the different model structures were measured via laboratory tests. The results indicate that the mud bricks (R1) had the lowest thermal conductivity with U=0.27 W/m.k, while the compressed soil bricks (R2) had the second thermal conductivity with U=0.3 W/mK, and the highest value of thermal conductivity corresponds to the burned clay bricks U=0.6 W/m.k. Figure 6. presents the microstructure characteristics of the developed bricks as explored by scanning electron microscope (SEM) for the brick samples used in models R0, R1, and R2. The SEM analysis was performed on the oven-dried fractured pieces, as shown in Figure 6. The SEM micrograph of the fired clay brick sample (R0). Figure 7a showed a relatively dense structure; however, some structural defects, including microvoids, which are uniformly distributed throughout the structure are obvious with small and homogeneous holes and cavities. These features are less apparent in the images of the bricks used in models R1, shown in Figure 7b, and R2, shown in Figure 7c. The microstructure of the mud-brick and the compacted brick matrix exhibited larger pores/cavities and possessed natural fibers of fine pores which help reduce the thermal conductivity coefficient, increase the thermal resistance, and thus minimize the heat flow into the buildings. This lower thermal conductivity plays an important role in improving the energy efficiency of buildings especially, in hot weather regions. These holes and cavities result in the low thermal conductivity of the mud and compacted bricks compared with fired clay brick. These results are consistent with other studies on mud and compacted bricks [63,64].

Figure 8. illustrates the difference in the temperatures of the internal and external surface of the bricks (the external surface temperature - the internal surface temperature) in making up the southern wall of the models R0, R1, and R2. The results show that the mud bricks with waste added in the model (R1) lead to the highest difference in temperatures between the external and internal surfaces with an average of 4.3 K. The compacted bricks (R2) lead to a difference in the temperature of the external and internal surface of 4 K on average. The burned clay bricks used (R0) lead to the lowest temperature difference (2.1 K) during the test periods. This confirmed the results of the thermal transmission of the brick models**.**

a) Clay bricks sample (R0) b) Mud bricks sample (R1) c) Compacted bricks sample

Fig.6. SEM images of the brick sample: a) Clay bricks (R0), b) clay bricks (R1), and c) compacted bricks (R2).



a) Clay bricks sample (R0) b) Mud bricks sample (R1) c) Compactedbricks sample

Fig.7. Photomicrographs of the surface of the brick samples used in the SEM characterizations

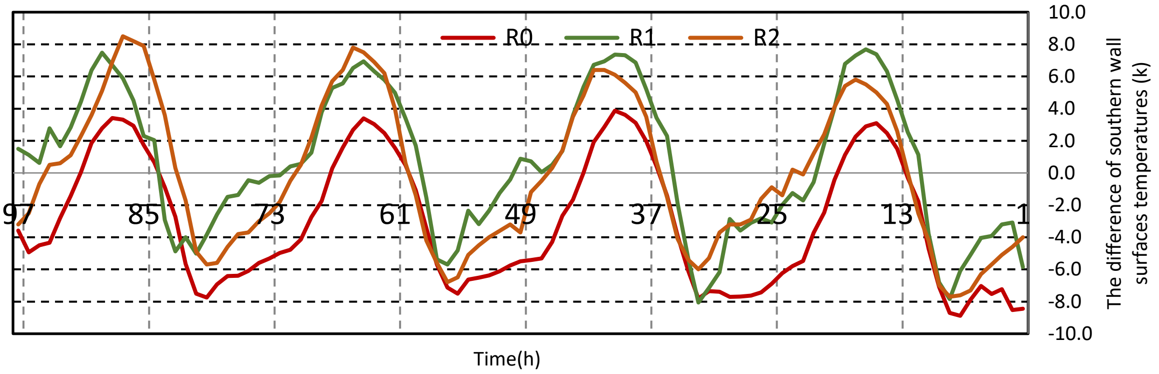


Fig.8. The difference in temperature between the external and internal surface of the south-facing wall for the reference model R0, R1, and R2.

Figure 9 shows the difference between the external and internal surface temperatures of the bricks used in the southern wall of the models R1 and R2 compared with the reference model, R0. It could be conducted that the clay bricks used in the southern walls of the R0 model lead to the lowest value of linear regression R2 = 0.08, whereas the mud bricks (R1) lead to a linear regression value of R^2=0.23. This finding indicates that the difference in the temperatures of the southern surface positively affects the internal temperatures of the models and leads to a lower internal temperature compared with the reference model throughout the experiment. Figure 10. shows that the compacted bricks used in the southern walls of model R2 lead to a linear regression value of R^2 = 0.32 whereas the fired bricks used in the southern walls of the (R0) model lead to the lowest degree of linear regression value R^2 = 0.07. This finding that the difference in the temperatures of the southern wall surfaces positively affects internal temperatures observed in the model R2 and leads to lower indoor temperatures than those observed in the reference model (R0) over the measurement period.

a) the reference room R0

b) the first room R1

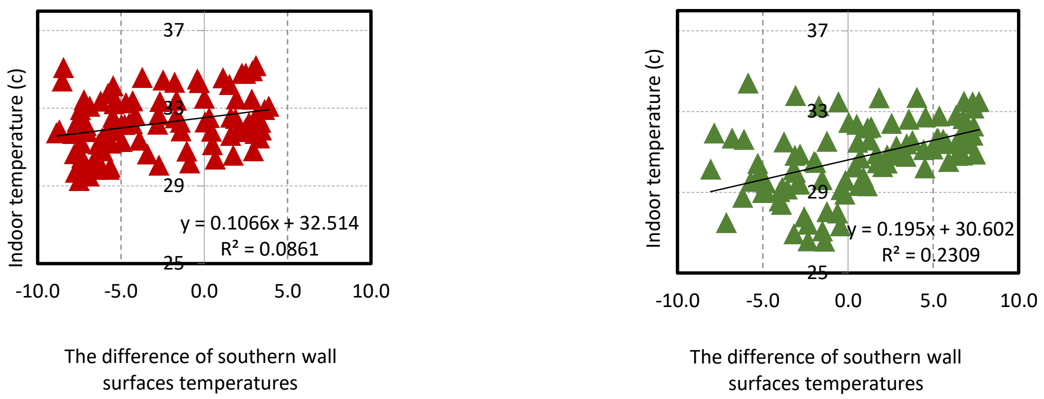


Fig.9. Linear regression pattern for the internal temperature and difference between inner and outer surface southern wall temperatures for R0 and R١.

a) the reference room R0

b) the second room R2

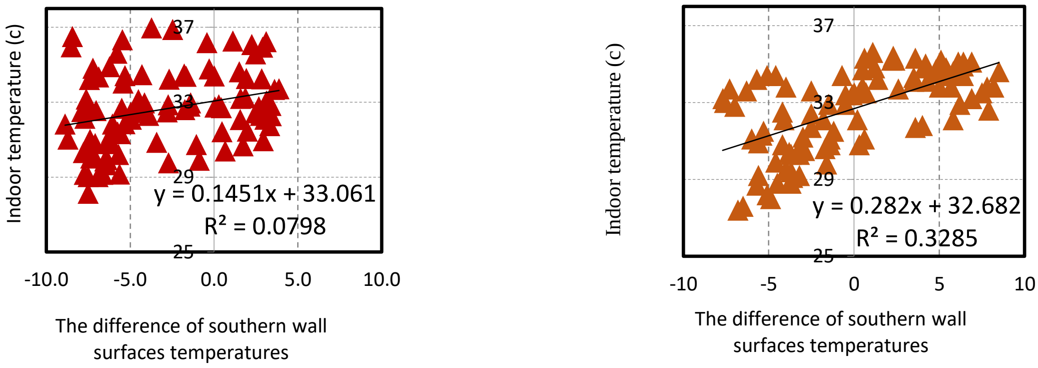


Fig.10. Linear regression of the internal temperature and difference between the temperatures of the surface of the bricks in the southern wall of R0 and R2

The difference in temperatures within the models is also due to the difference in the thermal properties of the southern walls, including the heat resistance and the ability of the material to absorb and lose heat; these properties were investigated via laboratory measurements. Figure 11 shows the linear regression between the indoor and outdoor temperature for models R0 and R1. The results show that the burned clay bricks (R0) lead to a linear regression of R^2 = 0.29 and correlation coefficient r =0.54; this value can be compared with the mud-brick with waste material additives (R1) that leads to a linear regression of R^2 = 0.47 and correlation coefficient r =0.69. It can be observed from Figure 11 that the indoor temperature in R1 was within the thermal comfort range according to the acceptable range for thermal comfort in naturally ventilated buildings based on the ASHRAE 55 standard [65,66]; the internal temperatures were within this range about 25% more compared with the reference case (R0). Figure 12 shows the linear regression between indoor and outdoor temperature for models R0 and R2. The results show that burned clay bricks lead to a linear regression expectation of R^2 = 0.46 and correlation coefficient r =0.68 which can be compared with the compacted bricks with waste material additives (model R2) that lead to a linear regression of R^2 = 0.27 and correlation coefficient r =0.52; this can be seen to lead to an increase to the acceptable range for thermal comfort 15% compared with the reference case (model R0).

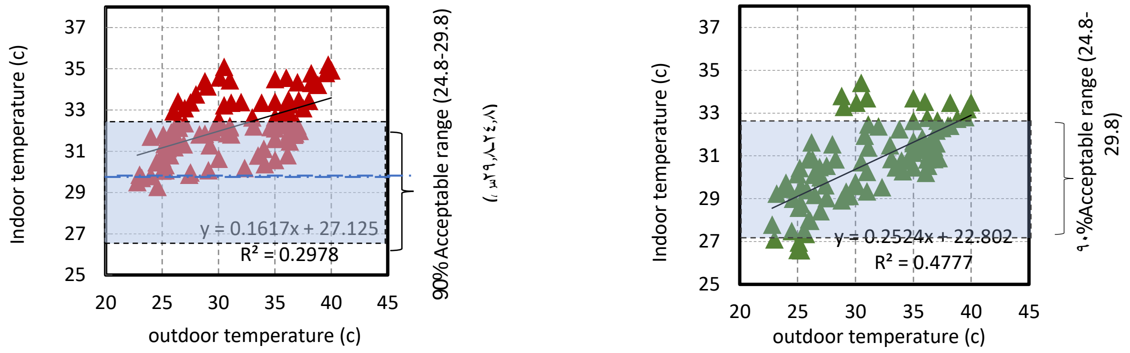

a) the reference room R0
b) the second room R1

Fig.11. Linear regression pattern of the indoor and outdoor wall surface temperatures for R0, R1.

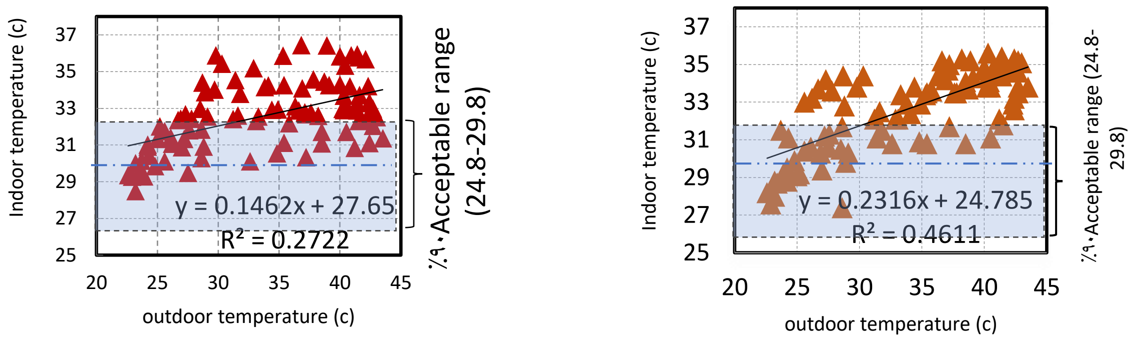

a) the reference room R0
b) the second room R2

Fig.12. Linear regression pattern of internal and external wall surface temperatures for R0, R2

4. Conclusion and recommendations

This study has examined the effect of using waste products and natural materials in the bricks used to construct the southern wall on the thermal behavior of residential buildings. The results of the experimental and analytical study showed that:

- Mud bricks (constructed from mud, rice husks, sand, and cement) improve the thermal performance and decrease the indoor temperatures to approach the acceptable thermal comfort limits by 90% with the acceptable thermal comfort limits according to ASHRAE 55 standard with 25% while the compacted brick (constructed from clay, rice husks, sand, and cement) leads to an improvement in thermal heat performance by 15% with the traditional (burned clay) bricks.

- The indoor temperature of the test rooms in which mud bricks were used meets the acceptable comfort range for 90% of the trial duration and led to a maximum internal temperature of 32.2°C. In the case of the reference model, a maximum internal temperature of 36°C was observed.
- The indoor temperature in the test model in which compressed soil bricks led to a maximum internal temperature of 34.6°C, whereas the reference model led to a maximum internal temperature of 37°C.
- The average difference between the external and internal surface of the southern wall surface was found to be 2.1 K in the case of the burned clay bricks, whereas the difference was 4.3 K in the case of the mud-brick and about 4 K in the case of the compressed soil bricks.
- Natural and waste (rise ash) materials were found to enhance the thermal performance of the bricks with holes and cavities. These features led to a lower thermal conductivity for the mud and compacted bricks compared with the fired clay brick.
- Natural and waste materials were found to reduce the temperature of the internal wall surface and the indoor temperature. The compacted brick that contained rice husk waste had a thermal conductivity of U=0.32 W/m.K. This value was higher than the thermal conductivity of mud soil brick that contained rice husk waste with U=0.27 W/m.K. These values can be compared with that obtained for the burned clay bricks for conductivity with U=0.6 W/m.K.

The study emphasizes the importance of research to promote natural materials and waste products in the construction of bricks especially in Egypt in new cities; the findings may be dependent on the environment and the available recycled waste products in each region.

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