The impact of thermal mass on building energy consumption: A case study in Al Mafraiq city in Jordan

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The impact of thermal mass on building energy consumption: A case study in Al Mafraq city in Jordan

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Abstract: This research discusses the usage of thermal mass of construction materials to produce comfortable thermal indoor environment and to reduce energy consumption for cooling and heating. What motivated this research is the disappearance of traditional construction methods and materials, such as thick stone and clay walls. Stone is used as a coating material in new buildings, but little attention is given to its significant thermal properties. These construction methods which are ideal to perform as thermal masses are becoming extinct in modern buildings. To achieve this aim a test of thermal mass efficiency is conducted on a case study building which consists two parts of different thermal mass under same climate condition in Jordan. Indoor temperatures of two rooms; one with clay walls; and a second room with concrete brick walls are measured at day and night times in summer and winter. Findings indicate that in hot and cold climates, the temperature inside the room of clay walls are kept within the human comfort zone, unlike the temperature in the room with concrete walls, which was not in the human comfort zone by 5°C. Results are recorded and analyzed to draw useful insights and recommendations. This research concludes that construction materials of high thermal mass, such as clay-bricks, significantly keep the indoor environment within the human thermal comfort zone. Thus, the energy required for maintaining the thermal comfort of the room is greatly reduced.

Subjects: Environmental; Environmental Health; Heritage Management & Conservation

Keywords: thermal mass; building energy consumption; cooling and heating; green buildings

ABOUT THE AUTHOR

Firas Sharaf, has a Ph.D. in Architectural Engineering, and teaches at the University of Jordan. The thermal mass topic lies within my research interests and publications in the field of green and sustainable architecture.

PUBLIC INTEREST STATEMENT

This paper investigates the use of thermal mass as a construction material to reduce the energy consumption. The author concludes that thermal mass is effective in improving comfort temperatures in buildings that experiences high daily temperature fluctuations. The use of materials of high thermal mass, such as mud and stone can play an important role in major reductions to energy use in heating and cooling systems. Thermal mass is most advantageous in hot climates where there is a big difference in outdoor temperatures from day to night.

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1. Introduction

Buildings and transportation form the greatest share of energy consumption worldwide as the total world fuel consumption in 2019 has increased by 2.9% (Jrew et al., 2019). The energy shortage is evident by increasing prices of fuel. The impact on average citizens takes a form of unbearable costs for heating, gas, and transportation, food, etc. (Abdalla, 2020). Buildings consume about 40% of global energy, and they emit approximately one-third of greenhouse gas (GHG) emissions. Heating and cooling of buildings account for more than 50% of energy consumption (Sharaf, 2018; Sharaf et al., 2016). Population growth, prosperity, and higher urbanization fuel building and construction activities and increase energy demand and global warming (Wahba et al., 2018). Residential and commercial buildings consume approximately 60% of the world’s electricity (Ellabbon et al., 2014; Roy & Das, 2018). The Sustainable Development Goals aim at integrating issues related to the local environment, climate, and economic frameworks (Sharaf & Al-Salaymeh, 2012). Global efforts to decarbonise and enhance energy efficiency in the world include buildings that offer great potential for achieving significant energy and GHG emission reductions, at least cost (UNEP, 2019). Additionally, building sustainably will result in healthier and more productive environments (Salvia, et al, 2019).

Energy consumption in buildings can be reduced by using a property of the mass of building known as “thermal mass,” which enables it to store heat providing “inertia” against temperature fluctuations. For example, a large thermal mass within the insulated portion of a house can serve to “flatten out” the daily temperature fluctuations, when outside temperatures are fluctuating throughout the day. Thermal mass absorbs thermal energy when the surroundings are higher in temperature than the mass, and give thermal energy back when the surroundings are cooler, without reaching thermal equilibrium (Brambilla et al., 2018).

Building materials and building elements such as walls, ceilings, floors, windows, doors, and ventilation systems play an important role in the process of equating heat between inside and outside of the building. Walls and ceilings, for example, together account for 60% of heat leakage in buildings when they lack good thermal insulation. There are more heat leaks through other building elements if they are not properly insulated. The lack of control over the heat exchange process between the building and its external environment leads to energy consumption in the building, in order to provide indoor temperatures suitable for users (Sadineni et al., 2011).

Energy is used in heating and cooling to compensate for the thermal losses caused by thermal differences between the inside and outside of the building to reach the level of internal thermal comfort appropriate for users. The problem arises when designers fail to address the issue of sustainability and to achieve active and passive thermal solutions in buildings, particularly thermal mass and thermal insulation (Damirchi Loo & Mahdavinejad, 2018; Lam et al., 2008). Not considering thermal mass properties of the building construction materials and sufficient thermal insulation will increases energy consumption in the building (DEFRA, 2016).

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This research study the thermal mass performance of the building to achieve a thermal comfort range, with less cooling and heating loads and energy consumption. The methodology leading this investigation is presented in the next section.
2. Methodology
This study aims to evaluate the thermal mass efficiency of construction materials in improving the thermal performance of buildings to achieve human thermal comfort with less energy consumption. The methodology adopted in this article to study the thermal mass efficiency in buildings is: a survey of the relevant literature to form a good understanding of the effect of thermal mass in reducing energy consumption in buildings; Conducting a case study of a building consisting of different parts with different thermal masses and testing them in the same climatic and thermal conditions. The location of the case study building was chosen in the city of Al Mafraq, in northern Jordan, with a semiarid climate suitable for thermal mass testing. The building has an old part made of clay-brick walls of 40 cm thick and wood rafters ceiling. The other part of the building is made of concrete brick walls of 10 cm thick and concrete slab with 2 cm cement plaster on the walls and slab. Architectural drawings of the building and detection of the building materials are required. A room in each part of the building was determined to conduct measurements of the daily temperature fluctuations using a thermometer device. The temperature in the two rooms was measured in cold weather conditions in November and December and in warm weather conditions in July and August in 2018. The time of measurements was at the heat rise at 1 pm and a lower temperature at 9 pm. The temperatures are recorded and documented in both rooms and a comparison is made between thermal fluctuations of inner and outer air of the building and with consideration to the human thermal comfort zone Figure 1. The residents of the house are asked about the indoor environment and heating methods they use. Data is analysed and presented in charts and tables. Figure 1 shows a diagram explaining the methodology and analysis chart. The comparison of thermal fluctuations of inner and outer air of the test rooms and temperature proximity or distance from the human thermal comfort zone is presented in graphs as Figure 1.

Effect on indoor temperatures in a residential building fluctuations of inner and outer air of two test rooms in comparison with thermal comfort zone.
This paper focuses on thermal mass as an important element of the thermal performance of a building. Different building materials have different thermal masses and thermal transition happens through the components of the building. To form a good understanding of how thermal mass works, it is useful to review the literature on thermal mass characteristics of materials and heat transfer methods in buildings (Zhai & Previtali, 2010).

3. Thermal mass of building materials

Building materials of high thermal mass capacity and ability to sustain internal suitable climates, such as clay bricks and masonry have been used widely in hot climate regions (Rapoport, 1969). Methods to reduce the amount of consumed energy depend on understanding factors that affect the thermal design of buildings, such as thermal performance of building materials and thermal insulation. The usefulness of materials for thermal efficiency is based on the relationship between their thermal properties and the thermal cycle that they are required to moderate. Thermal mass requires high specific heat capacity, high density, and thermal conductivity that means heat flows into and out of the material are aligned with the thermal cycle of the occupied space (Yu et al., 2009). Materials such as concrete and clay brick tend to have a useful thermal mass, whereas timber is a too slow absorber of heat, and steel has a too high a thermal conductivity. The ability of a material to absorb and release heat through thermal cycles is described as admittance or thermal mass and is based on its thermal capacity and conductivity, density, and thickness (Venkiteswaran et al., 2017). The factors that determine the thermal mass of materials are:

- Thermal capacity: the amount of thermal energy needed to increase the temperature of a kilogram of material by 1°K.
- Density: depends on the mass (or weight) per unit volume. The relationship between density and thermal mass is positive; it increases with the increase of thermal mass. Density measurement unit is kg/m³.
- Thermal conductivity: measures the property of material to conduct heat. It is preferable for thermal conductivity to be moderate in relation to materials with high thermal mass to ease the process of thermal absorption and releasing it in a way which synchronizes with the cooling and heating cycle of the building. Thermal conductivity is measured in watts per meter Kelvin (W/mk).

It is essential to differentiate between thermal mass and thermal insulation. In thermal insulation, the transmission of heat from inside or outside the building is blocked. The thermal mass maintains the heat but retransmits it to either inside or outside the building over a certain period of time and creates equilibrium of comfort temperatures between day and night (Bansal et al., 1994).
However, thermal mass works with insulation to reduce thermal transfer, so it requires less insulation in a thermal mass solution than in a stud wall solution (Sharston & Murray, 2019). For example, a typical wall R-Value requirement of R-18 might be met by a high-thermal-mass masonry wall with an R-Value of R-7 (ASHRAE, 90.1 2019).

4. Heat transfer in buildings
Heat transfer is a process of interchange or thermal flow that flows from hot to cold entities. Heat transfer happens when there is a difference in temperature between two spaces, such as inside a building and its surrounding. Hot air moves from highest temperatures side to lowest until both sides acquire the same temperature (Figure 3). Heat transfers in different ways such as conduction, convection and radiation (Kim & Viskanta, 1984).

Thermal conductivity is a material property that describes ability to conduct heat. Thermal conductivity can be defined as “the quantity of heat transmitted through a unit thickness of a material in a direction normal to a surface of unit area due to a unit temperature gradient under steady state conditions.” Thermal conductivity unit is [W/(m K)] in the SI system (Newell & Tiesinga, 2019). Heat conduction happens through building materials such as walls, ceilings, and windows. Heat flows from inside to outside of the building in winter and from outside building to inside in summer. Heat flow through conduction is affected by wall thickness and temperature differences on both sides of the wall, the material of the wall and its thermal conductivity coefficient k (Iyengar, 2015). The thermal conductivity coefficient k represents the flow of energy per unit of time. The k value depends on physical properties of the material, water content, and pressure on the material. It is measured in watts per meter Kelvin (or degree) (W/mK) (Newell & Tiesinga, 2019. In general, the material with a large k value is a good heat conductor and with a small k value is a good heat insulator and reduces the amount of heat transfer between the inside and outside of the building (Zong-Xian; Zhang, 2016). Table 1 shows k value

![Figure 3. Heat exchange mechanism during summer and winter throughout daytime, to and from the building.](image)

| Material          | Heat Transfer Coefficient k W/(mk) | Density (kg/m²) |
|-------------------|-----------------------------------|-----------------|
| Stone             | 1.7                               | 2300            |
| Solid concrete    | 1.13                              | 2000            |
| Raw clay brick    | 0.51                              | 700             |
| Masonry brick     | 0.7-0.8                           | 500             |
| Cork sheets       | 0.05                              | 300             |
| Polyester sheets  | 0.04                              | 20              |
| Wood              | 0.13                              | 600             |

Conductive heat transfer q is expressed with Fourier’s Law’s as:

\[ q = (k/s) A \Delta T = \text{heat transfer (W, Btu/h)} \]

\[ q/A = (k/s) A \Delta T = \text{heat transfer per unit area (W/m², Btu/(hr ft²))} \]

k = Thermal Conductivity of material (W/mK or W/m C, Btu/(hr ft °F))

s = material thickness (m, ft)

A = heat transfer area (m², ft²)
of different materials, for example, the $k$ value of raw clay brick is 0.51 W/(mK), this means that raw clay brick is better thermal insulator that stone which $k$ value is 1.7 W/(mK).

$$dT = t_1 - t_2 = \text{temperature gradient—difference—over the material (C, F)} \ (Bergman et al., \ 2019).$$

If heat transfers through a clay wall of 40 mm thickness and a thermal conductivity of 0.51 W/m, through 1 m² of the wall, and the temperature on one side of the wall is 30°C and on the other side is 20 °C. The conductive heat transfer ($q$) from this wall is calculated as: $q = [(0.51 \ \text{W/m °C})/(0.40 \ \text{m})] (1 \ \text{m²})(30^\circ\text{C})- (20^\circ\text{C}) = 12.7 \ \text{W, Btu/h (watt, British thermal unit/hour)}. Likewise, $q$ of a brick wall of a 0.15 m thickness = 50 W, Btu/h. An inverse relationship is observed between the thermal mass of the material and the thermal conductivity. If the thermal mass is large, then the thermal conductivity of the material is low, and if the thermal mass is small, the thermal conductivity increases.

If the air reaches a cold surface, its temperature will decrease, and as a result, its density increases and moves downward. Likewise, if it reaches a hot surface, its temperature increases and rises to the top. This phenomenon is called high airflow or heat transfer by convection, which increases with the increased coefficient of convection. This is related to the speed of the air’s connection to the wall. The amount of heat transferred through the wall will be greater if the air attached to the wall is mobile. If a layer of thermal insulation is added to the wall it will damp the air mobility and will decrease the amount of heat transfer. Also, the amount of heat transferred by conduction through the insulation material will be less due to its low heat conductivity. On the other hand, heat transfer by radiation transfers heat between entities without an interface or materials and heat can be transferred to the building by radiation. An ideal thermal design of buildings should consider heat transfer methods and the relation with the thermal mass of the building materials to reach the human thermal comfort range with less energy consumption (Bird et al., 2007; Rowley & Algren, 1937).

5. Human thermal comfort zone

Human comfort zone is defined as “the sum of thermal conditions surrounding the human, in which he feels pleased and comfortable, taking into consideration a number of factors, such as the temperature, humidity and air movement. Thermal comfort ranges maybe calculated for each climate zone using psychometric charts based on Adaptive Comfort standards (ASHRAE Standard 55, 2010). This enables designers to create indoor climates that occupants find pleasant (Figure 4).
Thermal comfort is attributed with four factors which together create a comfortable environment; these factors are air temperature, relative humidity, human efficiency and clothing insulation. Humans generally feel comfortable between temperatures of 22°C–27°C and a relative humidity of 40%–60%. Human body loses extra heat from its surrounding in different ways, such as sweating. The effort a human body makes to lose extra heat put stress on the body and makes one feel tired and encounters performance difficulties (Evans, 1980). Suitable thermal comfort range to improve user performance is achieved through proper interior environmental design to achieve adaptation between outer environment and building, depending on the energies and resources of renewable nature. Thermal exchange between a building and external environment happens through the building envelop which is the walls, roof, doors and windows (ASHRAE Standard 55, 2017).

6. Thermal mass of the building coat
A building cover provides thermal balance for humans through its design and materials. An important element of this balance is the thermal mass of the materials making up the building coat (Klepeis & Nelson, 2001). heavy thermal mass materials enable buildings to resist thermal fluctuations, also called “thermal flywheel effect.” Materials with high thermal mass can absorb external heat and store it, then transmit it to areas of lower temperatures. As a result, the thermal fluctuation and conductivity of the building decrease. This allows for more efficient heating or cooling in the building and less energy consumption (Granadeiro et al., 2013). Thermal mass is equivalent to thermal capacitance or heat capacity, which is the ability of a body to store thermal energy (Slee et al., 2014). It is typically referred to by the symbol Cm, and its SI unit is J/°C or J/K (which are equivalent). When using thermal mass for buildings the term “heat capacity” is used instead. The equation relating thermal energy to thermal mass is: \( Q = C_m \Delta T \), where \( Q \) is the thermal energy transferred, \( C_m \) is the thermal mass of the body, and \( \Delta T \) is the change in temperature (Halliday et al., 2018).

The increase of heat capacity of materials makes it ideal to use in buildings. Table 2 shows that solid concrete and adobe have high volumetric heat capacity, which provides ideal thermal masses suitable for climates with thermal fluctuation, such as desert climate. The way thermal mass works in buildings ensures the reduction of heating loads during winter and cooling loads during summer. Passive cooling methods, such as natural ventilation and canopies that protect the building from direct sun rays also help inner areas of the building to reach thermal comfort levels with less energy consuming (Figure 5; Givoni, 2011).

Internal temperature is also affected by internal thermal loads, such as lighting units, heat gained from electrical home appliances, and other appliances (Sharaf & Al-Salaymeh, 2012). During summer, particularly in hot regions, these factors cause thermal fluctuations. When the temperature reaches its highest level at afternoon hours, the building coat constructed from materials of high thermal

| Material                        | Heat capacity/unit volume \(\text{MJ/m}^3/(\text{Btu/ft}^3)\) |
|---------------------------------|---------------------------------------------------------------|
| Gypsum                          | 0.74 (20)                                                     |
| Concrete Hollow Bricks (Hollow 30%) | 0.74 (20)                                                     |
| Clay bricks (Adobe)             | 0.93 (25)                                                     |
| Solid Concrete                  | 1.04 (28)                                                     |
| White Oak                       | 1.27 (27)                                                     |
| Water                           | 2.32 (62)                                                     |
| Stone                           | 1.41 (38)                                                     |

Source: Bengtson, 2010
mass absorbs and stores heat. Heat needs time to reach inner areas of the building; this amount of time depends on the thickness of external walls and their thermal characteristics (Yu et al., 2009). The time difference between heat gain and release is called “Time lag,” which determines the efficiency of the thermal mass of the building materials. The longer time difference between storing the heat and retransmitting it inside the building, the more efficient the thermal mass effect. As a result, internal temperatures are kept within the human thermal comfort limits, which results in less heating and cooling loads and less energy consumption (Brown, 1990). Table 3 shows the time Lag of different construction materials of fixed thickness.

Lechner (2009) the use of materials with thermal mass is most advantageous where there is a big difference in outdoor temperatures from day to night (or, nighttime temperatures are at least 10 degrees cooler than the thermostat set point). Materials with the ability to enhance a building’s thermal performance provide one of the best passive design options and result in an integrated passive design strategy that balances building performance with heating and air conditioning requirements. Materials with thermal mass such as clay bricks (or Adobe) stone and masonry provide suitable indoor thermal conditions and pleasant atmosphere during summer and warm during winter, especially in areas with hot and dry climates (Fathy, 1986; Alaidroos, 2015). In cold climates, high thermal mass can cause an increase in energy use, which has implications for the design of buildings in cold climates, and contradicts the commonly-held assumption that high thermal mass is correlated with low energy use (Reilly & Kinnane, 2017).

7. The Case study house in Al Mafraq city in Jordan
The case study house is located in Mafraq city in the north of Jordan (Figures 6 and 7). The house has two parts, an old part made of clay bricks and an added part made of concert blocks.

Al Mafraq climate is semi arid, hot, and dry during summer and mild and humid during winter. January is the coldest month of the year in Mafraq area, as temperatures range from 5 to 10°C.

| Table 3. Time lag of walls of different building materials |
|-----------------------------------|---------------------|
| Material (thickness 30 cm)        | Time lag (hours)    |
| Adobe (clay brick)               | 10                  |
| Red bricks (standard)            | 10                  |
| Bricks (face)                    | 6                   |
| Concrete (heavyweight)           | 8                   |
| Wood                             | 20                  |
| Stone                            | 12                  |
Temperatures increase in summer, average temperature range reach up to 33°C (Figure 8). Extreme hot and cold temperatures in Mafraq city provide good comparison conditions of thermal performance of building walls made of different construction materials such as stone and rubble walls and concert bricks. A case study house is selected in Mafraq city which has rooms built of thick stone walls and rubble and rooms built of concert bricks. The maximum temperature diagram for Al Mafraq displays how many days per month reach certain temperatures (Figure 8).

There are 26.7 days in July and 27 days in August that have a temperature higher than 30°C (Figure 8). The sum of days with maximum temperatures exceed 30°C in a year is 120 days (from April to October).

8. Description of the case study house
The house is located in an old neighborhood in the market area of Al Mafraq city. The old rooms of the house were built clay bricks in 1938 and the additional rooms were built of concert brick in 1961 and 1977 (Figure 9). The house is still inhabited by the owner and his family and consists of four bedrooms, kitchen, bathroom, a courtyard and outdoor storage room for hay and barley (owner of the house Mr Makki Al-Maghrebi, 2018).
The construction materials of the old house are 40 cm clay bricks and ceiling made of wood rafters, steel beams and wooden shingles. Two rooms and a bathroom were built in 1977 of 15 cm cement bricks and concrete roof (Figure 10). Concrete was applied to the roof and to the clay walls to support them and to stop rain water leakage. Cement is applied on the old clay walls to stop erosion and capability to host insects inside cracks (Figure 11).
External doors of the house are made of iron; interior doors are made of wood. Windows are single glazed with wood or iron frames. Doors and windows condition is not efficient as they do not seal completely to stop air drafting efficiently and support indoor heat insulation (Figures 11 and 12).

Residents of the case study house were asked about difference in room temperature in the house. Replies indicate that clay rooms are warmer during winter and have nicer climate during summer than the rooms made of cement blocks.

In order to test the effect of thermal mass performance of clay and concrete materials on internal temperature under same climate conditions, two rooms in the case study house are selected. One room is made of clay walls of 40 cm thickness and the second room is made of concrete brick walls of 15 cm thickness. The ceiling is made of wood shingles in both rooms and both rooms are oriented to South East. Temperature measurements were conducted in lower outside temperatures in November and December and higher temperatures in July and August in 2018. Time of measurement was at 1 pm (13:00) and 9 pm (21:00). The device used to measure temperature is an electronic Thermo Meter (Figure 13).

9. Results and analysis
Figures 14 and 15 show that in lower outside temperatures, in Nov and Dec., temperature inside the room of clay walls was closer to human thermal comfort range than the concrete room, especially at night, as it was 5°C higher than the external temperature in average. Temperature in the room of concrete blocks was closer to external temperature throughout day and night. The residence of the case study house in Mafraq said that the rooms of clay walls in their house have comfortable climate than the concrete block rooms.

Figures 16 and 17 show that in a relatively high temperature atmosphere, in July and Aug., temperature inside the clay room during day and night was lower by about 5°C than the concrete
wall room, and temperatures in the clay wall room were closer to human thermal comfort range. This is caused by thermal mass effect as clay walls absorb heat at day time and gradually releasing it inside the room during night.
Residents of the case study house said that the rooms made of clay bricks in their house have a more comfortable climate than the rooms of concrete bricks, especially in the summer. The residents of the house were asked about the kind of heating they use in winter. They said they use gas heaters and that the rooms with clay walls consume one gas cylinder (12.5 kg) per week for heating an average of 6 hours a day. While heating the rooms with concrete brick walls consumes 1.5 cylinders per week. The residence also said there are negative characteristics of clay walls, such as tendency towards erosion and capability to shelter insects inside cracks.

More elaboration of the results in the discussion to further explore the effect of thermal mass on room temperature and the proximity to the human thermal comfort zone.

10. Discussion
The mud brick wall of the room (R1) is about three times thicker than the concrete walls in room R2 which indicates that thickness of construction walls is a significant factor of thermal
mass effect. Thickness of walls reduces thermal conductivity and enables heat storing, which give inner spaces more insulation from external heat effects. Heating and cooling loads are consequently reduced, which in turn reduces energy required for heating or cooling during the usage of building.

The comparison between the indoor temperature in R1 and R2 in Table 4 indicates that the $T_1$ day = 21°C is 10°C cooler than the outside temperature (OT) 31°C. $T_2$ day 25°C is 6°C cooler than OT. Thus, R1 temperature is 4°C cooler than R2 and in the human comfortable zone which requires less energy for cooling. At night, R1 is still cooler than R2 by 2.5°C as $T_1$-$T_2$ = 2.5°C. These result confirm the conclusions that thermal mass works well in hot climates (Section 6, Alaidroos & Krarti, 2015).

In colder temperatures in Nov. and Dec, the comparison Table 5 show that $T_1$-$T_2$ = −3, which means that indoor temperature of R1 is maintained warmer by 3°C during daytime, and 5°C at colder temperature at night. The results agree with existing literature that high thermal mass structures are likely to be effective in hot climates; however, in cold climates the effect is less.

The residents of the house were asked about the kind of heating they use in winter and energy cost. They said that heating room R1 which is of an area = 12 m² by a gas heater for an average of 6 hours a day for a week consumes around one gas cylinder (12.5 kg). The cost of a gas cylinder in Jordan is 7 dinars = 10 dollars, this is about 40 USD a month. Heating the room R2 consumes 1.5 cylinders/week, which is about 6 cylinders/month, with a total cost = 59. USD Thus, the increase in heating cost for R2 = 59−40 = 21 USD/month.

This analysis may differ taking into account other factors such as number of occupants, size and type of heater, insulation, windows and devices. Yet, quantifying cost differences of energy consumption of both rooms for cooling and heating is a way to demonstrate the effect of thermal mass on energy consumption.

| Table 4. Comparison between room temperatures in summer (July and Aug. 2018) |
|---|
| **Time** | **Outside Temperature OT** | R1: Clay brick room | R2: Concrete brick room | $T_1$ $T_2$ |
| 1 p.m. | 31°C | 31°C − 21°C = 10°C | 31°C − 25°C = 6°C | 10−6 = 4°C |
| 9 p.m. | 25°C | 25°C − 21°C = 4°C | 25°C − 23.5°C = 1.5°C | 4−1.5 = 2.5°C |

Td, Tn: average temperature at day or night

| Table 5. Comparison between room temperatures in winter (Nov and Dec. 2018) |
|---|
| **Time** | OT | R1 OT $T_1$ $T_2$ day = 20°C $T_{1\text{night}}$ = 17 | R2 OT $T_1$ $T_2$ d = 17°C $T_{2\text{n}}$ = 12°C | $T_1$ $T_2$ |
| 1 p.m. | 18.5°C | 18.5°C − 20°C = −1.5°C | 18.5°C − 17°C = 1.5°C | −1.5/15 = −3°C |
| 9 p.m. | 12°C | 12°C − 17°C = −5°C | 12°C − 12°C = 0°C | 0−5 = −5°C |

Heat transfer (Q) from the concrete brick wall is four times of the mud wall (50 Btu/h + 12.7 Btu/h = 4; sec. 4, pp.6). Heat transferred to the room R2 requires more energy for cooling than room R1 in summer. The amount of this energy is:

$Q_{\text{concrete}}$−$Q_{\text{clay}}$ = 50Btu/h−12.7 Btu/h = 36.3Btu/h. The Btu power difference for one month, assuming heat transfers for 6 hours a day = 36.3×6×30 = 6534 Btu/month. The power conversion formula of kW to BTU/hr is: $P_{\text{kW}} = P_{\text{BTU/hr}}/3412.142$ (www.rapidtables.com). To convert 6534 BTU/hr to kilowatts (kW): $P_{\text{kW}} = 6534$ BTU/hr/3412.142 = 1.915 kW. The cost of retail tariff of electricity in Jordan for households of the consumption block (161–300) kWh/month is 72 $s$.kWh = 0.15$/kWh (NEPCO, 2020). Thus, the cost of 1.915 kW = 0.15 × 0.1915 kW = 0.951$. The extra 36.3 Btu/h will cost about 25/month.
11. Conclusion
Thermal mass is often presented as a desirable feature of buildings and structures. However, the effects of thermal mass on energy consumption are poorly quantified in the existing literature. The methodology applied in this paper provides a way to quantify the effects of thermal mass in terms of energy and costs.

The experimental application shows that the method can provide useful quantitative results and provides a degree of insight and gives meaningful results when applied to an old structure. In this respect, the adopted method has significant potential. In terms of analysis, the results for a hot climate with large diurnal temperature variations show that reductions in energy use are possible; this is in agreement with accepted results regarding thermal mass. However, for cold climates where heating rather than cooling is the predominant concern, this analysis shows that thermal mass is not as efficient, and the drive towards high thermal mass structures in such regions warrants much further study before it is applied. As the two tested examples show, the thickness of a wall, is important. The same conclusions apply to both new-build construction and retrofit, and for cold climates, a thermal mass structural will perform as insulation from the outside temperatures. Further research may address construction materials of high thermal mass with less thickness.

More generally, for the equivalent overall conductivity, a design goal in hot climates ought to increase thermal mass, rather than a reduction in it. This study has looked at the heat flows only, and makes little allowance for the method of heating or cooling. The results presented here do, however, stretch beyond those of the particular wall types considered.

The authors carried out similar analyses for other locations and wall types, and similar wall types, with broadly similar results; and the method is applicable, in principle, to any type of construction to provide a quantitative analysis of the effects of thermal mass on energy consumption.

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