Reuse Waste Material and Carbon Dioxide Emissions to Save Energy and Approach Sustainable Lightweight Portable Shelters

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Abstract – Despite their great significance, lightweight structures have poor thermal inertia. In order to enhance the thermal comfort inside such buildings, architects need lightweight thermal storage. In this paper a model was used to experimentally investigate Heating Load profiles in lightweight shelters. The profiles were created for the climate in Jordan, then simulated for other climate zones. The proposed design concept was used to create a replacement for a thermal mass in lightweight structures such as shelters; by combining passive solar gain with energy storage embodied within the shelter floor (thermal-floor) to absorb solar radiation. This shelter design decreased the Heating Load during the winter season by acting as heat storage that releases energy at night time after being exposed to solar radiation during the day. The passive design depends on shading elements and overhangs shades to control solar gain during different seasons to prevent overheating during the summer. An experimental investigation of this model was performed to validate the simulation results. Validated simulation results showed that the designed thermal-floor is 25 % of the total shelter's floor area, which was crucial for obtaining favourable results. With CO₂ as a thermal mass, heat load was reduced up to 68 % compared to a 20 cm concrete slab floor. The use of this thermal storage material yielded a reduction in annual heating demand by 85 kWh/m².

Keywords – Comfort Zone; Jordan weather sustainability, lightweight shelter; thermal mass.

Nomenclature

ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers	
BIM	Building Information Modelling	
CO ₂	Carbon dioxide	
C_p	Heat capacity	J/kg·°C
E_h	Heating Energy demand	kWh
GHG	Greenhouse gases	
HDD	Heating Degree Days	
HDPE	High-density polyether	
PCM	Phase change material	
PMJ	Petroleum Jelly	
Q	Heat Load	W

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U	Fabric U-value	$\text{W/m}^2\text{K}$
U'	Overall building heat loss coefficient	kWK
Subfloor	A floor elevated and separated from the ground by an air gap	
ρ	Density	kg/m^3
η	Overall seasonal heating system efficiency	

1. INTRODUCTION

Buildings are an integral part of all civilised societies, yet they are the largest source of pollution. Researchers showed that a small sustainable change in buildings and employing energy-efficient techniques [1] have a great effect on greenhouse gases (GHG) emissions and global warming. Residential and commercial buildings' energy consumption on average increases by 1.5 % annually, and in 2016 buildings consumed 20.1 % of the global energy. The wider share of this Heating Load is related to heating, ventilation, and air-conditioning (HVAC) [2]. Buildings in Jordan accounted for 23 % of the total energy consumption in 2003 and are expected to rise in 2010 by 30 % [3]. While efforts to limit the emissions of greenhouse gases are considered in developed countries, economic growth in developing countries is causing an increase in emissions; these emissions must be reduced by utilising climate-friendly technologies [4].

Lightweight buildings, such as shelters, have great significance for such countries as Jordan, which is experiencing a refugee crisis [19]. Moreover, climate change is expected to bring a significant pattern of refugee migration among the developing countries, this migration is called environmental refugees [20]. This sustainable shelter provides an adaptation technique for such crises. However, a lightweight building has low thermal inertia and its indoor temperature is affected vastly by the outdoor ambient.

A thermal mass is comprised of thermal materials that have the ability to absorb the heat, and to store it to be released later. A thermal mass includes the envelope of buildings, internal walls, furniture, etc. [5]. Thermal masses in buildings store the heat, which transfers from the hot side to the cold side. When thermal masses absorb and store the heat, they lead to temperature lag between internal and external spaces. When the air around a thermal mass cools down, the heat stored within it will be released [6]. A thermal mass determines the capability of the building to store the heat energy, whether sensible or latent. Therefore, a thermal mass has a great effect on indoor temperatures, power consumption, and residential comfort. Parameters that affect the performance of thermal mass were concluded by [5], including the heat storage capacity, the surface area of thermal storage, the diurnal heat capacity and the layer thickness [5].

Some architecture designers think that the presence of thermal mass is good, but when it is used inappropriately, it could increase the energy consumption instead of decreasing it. [7] had studied the influence of thermal masses in 2017 for a hot climate that experiences large variations in the diurnal temperature; the results showed that savings in the heating load are possible [7]. On the other hand, a thermal mass for cold climates, where heating is a dominant distress, demonstrated that a thermal mass is a drawback; altering the design goal in cold climates to reduce thermal mass and raise thermal insulation [2]. Buildings with a great amount of thermal mass will have extended preheating or precooling periods [8].

A thermal mass has multiple types that include but not limited to bricks, concrete, concrete blocks, and earth; those all have a high density and heat capacitance; thus, they are considered

good thermal materials for buildings. Carbon dioxide (CO₂) emissions in construction materials is an important issue, research indicates that the indirect polluting emission occurring outside the construction site holds energy intensity higher than direct emissions. Steel reinforcement and cement are good examples of indirect emissions that happen during the manufacturing process [9]. However, some phase change materials (PCMs) have thermal mass properties without the weight or thickness constraints like in concrete. PCMs absorb then release energy by melting or solidifying; including plasterboard, screed or paints and frequently include microcapsules of wax [10]. The location of thermal mass is of the utmost importance, for example, water tanks location could be employed to protect western walls since they will absorb solar radiation during the afternoon.

A thermal mass must be located in a way to counter passive solar gains. Otherwise it will absorb the room's heat in winter, making it colder. The best location for a thermal mass in winter is on the floors and walls that receive direct solar gain. Glass facade should be north-facing, if not, south-facing windows must be shaded. The shading must be designed to protect the thermal mass from the summer sun, at the same time it must allow winter sun to cross the space [11]. In summer, the thermal mass must be in well-ventilated rooms. Ventilation is needed to remove the heat absorbed during a summer day [12], otherwise it will continue to accumulate heat creating an oven effect throughout several hot days. Ventilation is better executed at night [13] and is called night purge [6].

A thermal mass, according to some literature, applied only to sensible heat storage. Yet, when PCMs are utilized as latent heat storage, they can raise a building's thermal inertia without using great amounts of material; hence a latent heat storage embodied within a lightweight element can perform like heavyweight elements in constructions [2]. One of the technologies that were developed to enhance the efficiency of renewable energy sources is thermal energy storage (TES) [8]. Sensible heat storage occurs in the form of temperature change in the medium such as water, oil, rock beds, air, concrete, bricks, and sand. Latent heat storage occurs when the heat is utilized from the phase transition like in PCMs. A high thermal capacity in a shaded and an insulated building can lower its indoor maximum temperature by 35–45 % compared to the outdoor temperature when the building is unventilated [14]. In 2017, a thermal mass resulted in 10–15 % energy savings for heating by mixing various types of thermal materials into the envelope of the building [15].

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Previous studies had investigated the performance of thermal mass for residential or commercial buildings. Thermal mass needs the combination of solar energy with thermal energy storage [8], which had not been tested in shelters yet. There is a deficit in research focusing on thermal mass performance in some climate zones such as low temperate and cold

zones [7]. Energy efficiency in the lightweight building was investigated by [2], [18], [19]. Thermal mass in the building was investigated by [6], [8], [18]. Up to the author's knowledge, thermal mass in the lightweight building was never investigated.

The goal of this paper is to investigate the possibility of reusing lightweight material; hence, PCMs and carbon dioxide; to replace traditional thermal mass inside lightweight structures, shelter, without increasing the structure weight significantly. Normally, shelters are constructed from a steel frame and a light insulation material and do not contain thermal masses. The thermal mass' material is usually heavy and can increase the shelter weight significantly, which limits its ability to be transported easily. This was achieved by investigating different materials that can perform as thermal mass for lightweight portable structures such as shelters. This paper investigates the effect of the thermal storage in the floor on the heating load required and heating demand as well. Since the thermal storage in the floor (thermal-floor) will contain materials such as carbon dioxide and petroleum jelly to dedicate polluting emissions and serve energy efficiency in lightweight structures.

2. METHODOLOGY

The thermal mass material in a lightweight structure – prefabricated shelter – was investigated experimentally to determine the best performing material during winter season. Experimental data were used to validate results found by *HvacLoadExplorer* software, the cooling/Heating Load calculation software that accompanies the Heating, Ventilating, and Air Conditioning [20]. This software was used to investigate the heating load of the shelter (Fig. 5 – Fig. 10) utilising the material with the best overall performance based on the experimental investigation.

The shelter design adopted for the experimental investigation is shown in Fig. 1. The thermal mass material was enclosed in the area labelled thermal-floor (Fig. 2). Materials with high thermal capacity and low density were expected to emulate the best thermal mass performance. Therefore, they were considered to be the optimal candidate for a portable shelter without increasing its weight.

Thermal floor experiment was done by testing a real model designed as shown in Fig. 1. The model was placed in a room cooled to 20 °C in order to create a controlled environment to apply the concept in a cold ambient; it should be mentioned that this experiment was done during summer months of 2017, July and August.

Thermocouples were used to measure the temperature; the readings were taken from a multi-meter. A *SEAWARD* radiation meter was also used to set the desired radiation of 500 W/m² for a period of five hours, which resembles winter sun hours in Amman, Jordan [21]. Thereafter, the temperature inside the shelter model, as well as the floor, for each tested material was measured using thermocouple sensors located in the center of the shelter's inner space also on the floor. Thermocouples were located according to methods of sensor distribution described by [22] and [23]. The results were compared to several floor materials such as tiles, concrete and metal decking that are common for caravans.

The design concept depends on a passive energy gain, combining large southern windows with thermal energy storage embodied within the floor reusing materials such as petroleum jelly and CO₂ to replace conventional thermal mass. This mechanism is validated during winter since the southern windows are shaded by an overhanging shade (Fig. 1), that allows low winter sun to penetrate the space and blocks summer sun that has a high angle, so the thermal-floor is blocked from summer radiation. In the summertime, the indoor thermal comfort was maintained through natural ventilation, which helps to carry the heat away. In addition to that, the shelter walls are completely insulated using polyether foam, and all the windows are double-glazed with low emissivity that has a high *R*-value up to 2.7 K·m²/W. Air Conditioning split unit is proposed to cool the space during hot days of summer. However, using energy-efficient measures such as overhang shading and natural ventilation, the cooling load will be decreased to the minimum, causing the air conditioning to work fewer hours more efficiently.

In winter time, large southern windows to capture solar radiation during the day were used. Then a part of the floor was filled with a PCM material, as listed in Table 1, to work as heat storage and to help decrease the heating load. Finally, high thermal insulation using expanded polystyrene with *U*-value 0.13 W/m²·K prevents major heat losses from the inner space, which will support the work of the air conditioning to provide heating up to the thermal comfort levels with less energy demand; the AC unit is to be fed from PV cells.

Materials were chosen also to have low density (kg/m³), so it can perform as a thermal mass without increasing the weight of the shelter. The thermal-floor block area is 4.8 m² with a 15 cm depth (volume = 0.72 m³), so the density will dominate the weight of this part when materials are compared in Table 1.

TABLE 1. EXPERIMENT MATERIALS PROPERTIES [10], [24]

Material	Heat capacity, J/(kg·K)	Density, g/cm ³	Melting Point, °C
Vaseline-Petroleum Jelly (PCM)	2.14–2.90	0.79–0.85	36
Paraffin wax (PCM)	2.14–2.90	0.896092	46
Graphite	0.71	2.09–2.23	–
Wax (PCM)	3.43	0.9	37
Water (PCM)	4.184	1	0
HDPE (high-density polyethylene)	2.25	0.93	–
CO ₂ gas at 100 kPa	840	–	–

3. RESULTS AND DISCUSSION

3.1. Thermal-floor effect on temperature

The main goal of the experiment was to track the behaviour of the material when subjected to radiation of 500 W/m² for 5 hours, which is the solar radiation in winter in Amman. Sensors were placed inside the shelter space and it was tested under controlled conditions. Fig. 3 and Fig. 4 track the temperature variations for each material, separately, from the starting point when the radiation is on, then radiation goes off after 5 hours and tracking continues until the

floor and the room cool down to room temperature. Low-density materials with high heat capacity (C_p), such as PCMs were examined and compared to tiles and concrete in Fig. 3. Additionally, materials that have bright colours such as Petroleum Jelly-Vaseline (PMJ) and paraffin wax were mixed with black paint to increase radiation absorption [6].

Fig. 3. Experimentally obtained thermal-floor temperature using suggested materials to function as thermal mass, compared to concrete and tiles.

Minutes after the solar radiation was turned on, the initial floor temperature of all measured materials was approximately the same with an exception of insulated white tiles that were one degree higher. Finally, when the solar radiation was turned off, the floor's temperature dropped rapidly back to its initial temperature. When water was used as a thermal mass, the floor's temperature at the start of the solar radiation was low, in comparison to the rest of the materials, but once the solar radiation was off, water maintained a relatively high floor temperature for a little more than one hour. PMJ yielded the highest floor temperature during exposure to solar radiation and maintained the highest floor temperature over a few hours after the solar radiation stopped. HDPE was able to absorb heat from the solar radiation quickly, but it did not store much energy as evidenced by the rapid decrease in the floor's temperature just after the solar radiation stopped. The thermal floor's behaviour was reflected in the room's temperature detected experimentally; this effect can be seen clearly in Fig. 4.

Fig. 4. The shelter model space temperature comparing thermal materials to concrete and tiles.

The installation of a thermal-floor into the shelter model was intended to capture energy from solar radiation in the winter season and heat the space (hence reduce heating load and energy demand for heating as well), while simultaneously store the energy and redeem it once the solar radiation ceases leading to a reduction in heat demand of the shelter. An additional measurement to the floor temperature is the space temperature of the shelter model, shown in Fig. 4, together they gave a better indication of the behaviour of the thermal-floor containing the thermal mass. PMJ yielded the highest space temperature while under solar radiation and relatively higher temperature once the solar radiation had stopped. HDPE had a similar profile to PMJ during and after solar radiation but its performance was weaker in comparison to PMJ especially when considering the space temperature from 1 to 4 hours. Concrete seems to need higher solar radiation; hence higher energy intensity to perform as an energy storage medium for the shelter model. Based on the measurements shown in Fig. 3 and Fig. 4 and given its low melting temperature and its ability to store the extra energy as latent heat then release it later, petroleum jelly PMJ mixed with black paint was selected as the thermal-floor material and will be used henceforth in this study.

3.2. Validation

Software analysis needs validation by experimental results before taking its results for granted to scientific researchers. *HvacLoadExplorer* was used by much previous research to conduct heating and cooling loads [25]–[27]. Simulation using *HvacLoadExplorer* depended

on defining each building element according to its thermal condition. This software uses the heat balance method (HBM) for calculating cooling and Heating loads in buildings. For heating load calculations, it uses the winter data of one day of the coldest month for each location for the calculation. The climate data were extracted from the ASHRAE Handbook [28].

The controlled environment room helped to prevent serious airflow through the model, which can add the effects of convective heat transfer. Even though convection must always happen even in a slight amount, and this certainly affected the temperature measured inside the model. Shelter model edges were perfectly sealed with polyether foam insulation, though it will not prevent the thermal leakage from heat bridges especially within opening spots, such as windows and doors.

Temperature results from the experiment shown in Fig. 3 and Fig 4 were used to calculate heating load variations in Eq. (1); the result found was compared with results generated from the program in Fig. 5.

$$Q = U \cdot A \cdot \Delta T, \quad (1)$$

where

Q heating load;

U U-value of the material that indicates the ability of the material to conduct heat through it;

A surface area of the shelter;

ΔT heating degrees needed for the inside of the shelter (taken from the experiment) to reach the comfort zone limit.

Fig. 5. Heating load value comparison between simulated and experimental calculations.

The model's elements material, wall, floor, and windows were defined to match the material used in the tested model. The heating load found from the experimental work was compared to simulation results. The simulation was performed based on two techniques. The first simulation was based on solar irradiance; direct solar irradiance on the southern wall was measured during the experiment. The second simulation was temperature base; the reference temperature was of the southern wall, which was subjected to radiation. During the experiments, outside wall temperature was measured using Laser Infrared Thermometer. The temperature reading was used in software to run the simulation. The simulation results were 93.8–99.5 %, which is close to experimented values. Validation results are illustrated in Fig. 5; the error between both results had been calculated, and its range was between 0.17 % and 6.8 % and the simulation for the solar irradiance case was more accurate than the simulation depending on the temperature difference. Based on the comparison between the simulation and the experimental results, it was concluded that the simulation is valid and the simulation-based on solar irradiance is more accurate. Thus, it will be used for the further investigation.

To consider other factors of error propagation, first, the Vaseline was exposed to 500 W/m² radiations twice; the overall percent uncertainty was ± 0.63 . Hence, the data between the two trials matched up to 92 %. The error was produced considering both instrumental uncertainties of the multi-meter that is ± 0.5 . The total relative uncertainty ranges from ± 0.6 –1.02. The experimental values were conducted twice and the relative error for the whole value readings was from 0.07–0.2. Finally, a sensitivity analysis was conducted to weight the effect of temperature error on heating load calculation, because the temperature was used to validate the load calculation software; as a result, the temperature will cause uncertainty of ± 15.06 watts in the heating energy demand, which is 6.64 % of the calculated value.

3.3. Heating load for the shelter in different climate zones

Heating Energy demand E_h and consumption (kWh/m² per year) mean annual specific needs and consumptions per net heated area. A building is heating energy needs means the energy required to maintain indoor air conditions. So Heating Energy demand is based on the building's heat losses that are represented here by heating load profiles.

The monthly heating energy consumption can be calculated by:

$$E_h = \frac{U' \cdot HDD \cdot 24}{\eta}, \quad (2)$$

where

- E_h Heating Energy demand, kWh;
- HDD Heating Degree Days;
- η overall seasonal heating system efficiency;
- U' overall building heat loss coefficient (kW/K), given by:

$$U' = \frac{A \cdot U + \frac{1}{3} NV}{1000}, \quad (3)$$

where

- U fabric U-value, W/m²·K;
- A component area, m²;
- N air infiltration rate in air changes per hour, h⁻¹;
- V volume of the space, m³.

The numerical factor $1/3$ arises from typical values of density and specific heat of the air and the conversion to air changes per hour [29].

The thermal-floor effect on the heating load was simulated in the coldest month of the year considering a one-day heating load, which differs accordingly to the location of the shelter. The system setpoint for heating was $25\text{ }^{\circ}\text{C}$ to make sure that the lowest temperature inside the shelter was no less than $22.2\text{ }^{\circ}\text{C}$ to comply with the comfort zone defined by the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) [30]. The shelter's model was also tested in different locations worldwide (Fig. 6) and implied good performances in temperate climates such as London, UK. Simulation results implied that in temperate regions thermal-floor would reduce the heating load by 16.7 % due to winters cold and the cloudy skies most days.

Fig. 6. Heating load for the shelter using PMJ material on the floor in different climate zones, each basic climate zone was represented by one city.

Temperate zones experience warm summers and cool winters in January at an average dry bulb temperature of $-1.2\text{ }^{\circ}\text{C}$ and relative humidity of 75 % [28], the use of thermal-floor reduced heating energy demand by 13 kWh/m^2 per year. A thermal mass during the day is expected to absorb the heat from direct solar radiation, then release it at night time [7]. Thermal mass in cold zones caused discomfort if it was placed improperly according to previous research that agrees with our results. From literature it was found that when a lightweight single-family house was built using the concrete floor, the thermal behaviour

became closer to heavyweight structure performance. For buildings with large window surfaces, 45 % of the floor's area, the heating load was reduced by 15 % [2].

A thermal-floor does not work efficiently in Polar Regions, the simulation was done for Toronto Canada, for January at an average dry bulb temperature of -5.6°C and relative humidity of 60 % [24]. Similar to what was reported in previous studies that for cold regions sustainable lightweight buildings depend on high insulation to be used in the structures [7], [15], this could be attributed to the very low temperature and low solar radiation angles, with overcast sky most days.

Arid climates, such as in Amman, Jordan, are the best zones for a thermal-floor with high solar insolation and cold winters. PMJ and CO_2 thermal-floors could reduce the heating load by 40–50 % (Fig. 6) because it has large diurnal temperature ranges between day and night. Yet, for the tropical hot humid climate with warm winters, a thermal-floor would cause overheating, because the thermal-floor stores heat during the day and are not ventilated creating an oven effect over many hot days.

3.4. Heating load and energy demand for the shelter in Amman, Jordan

The shelter's model was designed for Amman, Jordan, as an example of subtropics (arid) climatic regions. Subtropics regions experience hot spells and significant temperature differences between daytime and night-time. Jordan's daytime temperatures are beyond comfort zone yet at night time the temperature drops below the range of comfort zone. A thermal mass is expected to be an appropriate addition in the arid regions.

Fig. 7. Heating load of a shelter in Amman, Jordan, using different materials in the thermal-floor.

The shelter's heat storage (thermal-floor) performance was investigated in Amman using *HvacLoadExplorer*, which estimated the hourly heating load in Watts for the day of 21 of January at an average temperature of 6.6 °C and relative humidity of 83 % [25]. The simulation was performed for two cases. The first case was performed with a metal floor with no insulation simulated, and most of the time heating load was in the range of 500–1000 W, as shown in Fig. 7. The insulated metal floor in the second case showed better performance than the first case but it was less efficient than using other materials on the floor as thermal mass.

In a shelter designed with 4.5 m² thermal-floor, 40 % window to wall ratio PCMs reduced the heating load by nearly 22 W/m² compared to the metal floor. Essentially, if the shelter was not thermally insulated none of the above results would have been achieved. The results indicated that using paraffin, PMJ, or water as thermal-floor, reduced the Heating demand by 45 W/m² compared to a metal floor that would reduce the annual heating energy by 32 kWh/m².

3.5. Carbon dioxide in the thermal-floor

CO₂ is a well-known thermal storage material in concentrated solar tower technology for renewable energy for it has a high heat capacity when pressurized and low density in the gaseous state, 1.78 kg/m³ at room temperature [31]. CO₂ in three different forms, gas at 100 kPa, pressurized liquid, and pressurized gas, were examined as a thermal-floor and the results are shown in Fig. 8.

Fig. 8. Comparison of heating load for a shelter in Amman, Jordan between CO₂ and PMJ thermal-floors; Shelter design with 4.5 m² thermal-floor (25 % of the floor area), 40 % window to wall ratio.

Saturated CO₂ liquid reduced heating load from 30–50 % compared to tiles, yet saturated vapor has 241 kg/m³ density, and saturated liquid has 714 kg/m³. Both have density less than PMJ 840 kg/m³.

CO₂ and PMJ were also compared, as shown in Fig. 8, to tiles and concrete, which are the most common surfaces for floor construction worldwide. CO₂ performed better than PMJ in the shelter. The thermal-floor weighed 150 kg when saturated CO₂ vapor was used, 1.09 kg is the weight of CO₂ gas, and 149 kg is the weight of the container; while 529 kg of PMJ was needed to achieve comparable performance. Therefore, the CO₂ gas effect on the heating load was very close to that of PMJ, but with around 100 kg less weight.

3.6. Thermal-floor position and area effect on heating demand

The thermal mass is usually a wall or many walls working together, in this study, PMJ and concrete were tested as a wall and as a floor; both materials worked more efficiently as a floor and reduced Heating demand by 20–30 % compared to the same materials used in a wall. Different thermal-floor ratios were simulated for heating demand in the shelter model. If the whole floor were covered with PMJ instead of 25 % of the floor, it would cause a slight reduction in heating demand by 4 kWh/m² per year. A previous study demonstrated that the relationship between the amount of mass in the space and the ambient air temperature diurnal variation in the same space was an exponential relationship [32].

3.7. Subfloor

The floor can be designed in two different ways. In the first type the floor is directly connected to the ground, and so is affected by the ground temperature and the second type considers the floor is suspended (subfloor); such as walls, the subfloor is elevated and separated from the ground by an air gap. Both designs for subfloor were simulated for Amman, Jordan weather and results are shown in Fig. 9.

Fig. 9. Heating load value comparing subfloor and on a ground slab, Amman, Jordan.

For a shelter design with 4.5 m² thermal-floor of PMJ, 40 % window to wall ratio, the results in Fig. 9 show that when the shelter's floor is built on the ground it would lose some heat to the ground below the floor. Based on that the heating load was higher for shelter with a floor connected to the ground as compared to the subfloor design.

3.8. Window to wall ratio effect on Heating load

A passive design depends on combining a thermal mass and a solar heat gain by employing large south-facing windows. The window to wall ratio is a very important concept in passive heating, so the simulation of a different window to wall ratios was carried out. For a room that has insulated walls and floor, increasing the window area to wall area ratio from 20–80 % led to only 8 % heating load reduction (5 kWh/m² per year). Yet when it was combined with the thermal-floor (100 % of the floor covered with PMJ), increasing the window area to wall area ratio from 20–80 %, reduced the annual Heating demand from 27 to 7 kWh/m² (500–100 W) as indicated in Fig. 10.

Fig. 10. Heating load profile for the different window to wall ratios for PMJ thermal-floor in Amman, Jordan.

This shelter design had a 40 % window to wall ratio because in summer a large glazing facade is not convenient for all climates; it can be very suitable for the temperate zone with long winters and no major seasonal variations, but not suitable for other climate zones. Jordan is a subtropics (arid) climate it has cold winters but hot summers, so large windows would cause major heat gains and high energy demand for cooling in the summer.

4. CO₂ THERMAL-FLOOR ENVIRONMENTAL IMPACT

Since the goal of this study is to use a thermal-floor concept by employing recycled or reusable wasted products, it will help to save energy used for disposal, also it will help to create a new track for material residuals rather than dumping products in the environment. Nearly 670 kg of CO₂ equivalents are generated to produce 453.6 kg of HDPE. 79 % of the greenhouse gas emissions are associated with fuel and 21 % are related to manufacturing processes [33].

CO₂ is one of the nontoxic and non-flammable working fluids that has good heat transfer characteristics. CO₂ was commonly used in air conditioning and marine refrigeration as a working fluid, for it is not expensive and widely available [32], [33]. Therefore, instead of looking to CO₂ as a part of the problem causing a greenhouse effect, it could be considered a solution for thermal mass in a lightweight structure.

Low-carbon city [34] could consider low-carbon production and consumption in order to accomplish lower energy consumption and reduce CO₂ emission [35]. CO₂ can be extracted from combustion emission by available techniques, like conventional wet scrubbing and Amine scrubbing, then it can be reused in other ways [36]. A thermal-floor offers a good option for CO₂ to work as a thermal fluid causing a micro greenhouse effect within the floor and reducing heat demand; instead of releasing CO₂ to the atmosphere or injecting it in geological reservoirs. Table 2 summarises all the results discussed in this study.

TABLE 2. RESULTS SUMMARY, THERMAL-FLOOR PERFORMANCE IN SUBTOPIC CLIMATE, AMMAN, JORDAN LOCATION

Passive design techniques	With thermal-floor	Without thermal-floor
Window to wall ratio	Increasing the ratio from 20 % to 80 % reduces the Heating demand by 18 kWh/m ² per year.	Increasing the ratio from 20 % to 80 % reduces the Heating demand by 6.5 % only.
Subfloor vs. floor on the ground	Thermal-floor combined with subfloor (floor elevated from the ground) reduces the heating demand by 27 kWh/m ² per year.	Subfloor only reduces the heating demand by 7 kWh/m ² per year.
Thermal mass Material (cover 25 % of floor area)	Both PMJ and CO ₂ gas (at 100 kPa) reduced the energy demand for heating by 50 % compared to concrete. PMJ reduced the heating demand by 31 kWh/m ² per year when compared to insulated tiles and by 29 kWh/m ² per year compared to a 20 cm concrete slab floor. CO ₂ reduced the heating demand by 85 kWh/m ² per year compared to a 20 cm concrete slab floor.	
Area of thermal-floor	Increasing the thermal-floor area from 25 % to 100 % of the total shelter area reduced the Heating demand by only 3 kWh/m ² per year; it has an effect because only a certain part of the floor is subjected to the solar radiation coming from the southern window and this part will function as a thermal storage.	
Internal vs. external thermal mass	Internal mass, whether it is a wall or floor reduces Heating demand. An internal wall of (PMJ) reduces Heating demand by 4 kWh/m ² per year compared to the external wall of (PMJ), and (PMJ) floor reduces the Heating demand by 11 kWh/m ² per year compared with the external wall of (PMJ). Considering the wall or the floor to be entirely covered with (PMJ).	

5. CONCLUSION

This research investigates the thermal mass for a prefabricated lightweight shelter by replacing the traditional thermal mass with lighter materials, hence PCM and CO₂ *Hvacloadexplorer* software validated by experimental data is used to improve thermal comfort in lightweight shelters with PCM for different climate zones. Results showed that PCM could effectively control the indoor temperature rise and temperature fluctuations. The most favorable results were achieved when PMJ was used in the thermal-floor in a 20 cm thick subfloor covering 25 % of the total floor area of the shelter model. Southern facing windows, covering 40 % of the wall area, were utilized to capture the winter's solar radiation. Initially, the thermal-floor was investigated for the four main climate zones: tropic, subtropics (arid regions), temperate, and cold. Evaluating the performance of the shelter's model in temperate climates, such as London, UK, the thermal-floor reduced heating demand by 13 kWh/m² per year. The thermal-floor did not work efficiently in polar cold regions, which could be attributed to the very low temperature and low solar radiation angles. Yet, for the tropical hot humid climate with warm winters, the thermal-floor had a negative effect and caused overheating creating an oven effect over many hot days. However, arid regions were the best zones for a thermal-floor with high solar insolation and cold winters. PCM and CO₂ floors reduced the heating load by 40–50 % given the diurnal temperature ranges between day and night. Both PMJ and CO₂ gas reduced the heating energy demand for heating by 65–85 kWh/m² per year compared to concrete. PMJ reduced the heat demand by 31 kWh/m² compared to insulated tiles, and by 56 kWh/m² compared to concrete. CO₂ reduced the heating demand by 85 kWh/m² compared to a 20 cm concrete slab floor. When the thermal-floor was combined with subfloor (floor elevated from the ground), it reduced the heating demand by 27 kWh/m². Internal mass whether it was a wall or a floor reduced the heating load, which is based on the building's heat losses. PMJ internal wall reduced heat demand by 4 kWh/m² and PMJ floor by 11 kWh/m² compared to the external wall of PMJ. Increasing window to wall ratio from 20 % to 80 % reduced the heating demand by 7 kWh/m² only but when combined with internal thermal mass (thermal-floor), under the same ratio, the heating demand was reduced by 22 kWh/m².

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