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Effect of thermal mass of insulated and non-insulated walls on building thermal performance and potential energy saving

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Abstract. The presented study aims to evaluate the effect of thermal mass in heavyweight construction in residential buildings in Palestine on indoor thermal environment using a building performance simulation tool. The most used residential building types, shapes and sizes were used as typical models for indoor environment performance simulation. The paper used a sensitivity analysis for four different scenarios according to the location of thermal insulation in the wall for two climatic zones, when no heating and cooling was used. The building material's thermal properties, infiltration, activities, time schedule, electric lighting and glazing selection were based on onsite studies. The results show that the internal thermal mass of the studied buildings influences their thermal performance and future potential energy demand for heating and cooling. Buildings with insulation positioned on the outside, with high thermal mass and high thermal time constant showed the best thermal performance for different climatic zones, whereas buildings without thermal insulation or with insulation from the inside showed the worst thermal performance. The position of thermal insulation will affect potential energy demand for heating and cooling in the residential buildings.

1. Introduction

Due to their cooling and heating requirements, buildings are major contributors to energy consumption worldwide. A major part of the energy consumed by air conditioning is due to heat transmission through exterior walls. Therefore, reducing this load becomes one of the most effective energy conservation measures in buildings. The use of special building materials, thermal insulation, as well as employing good design practices should serve this goal [1]. The need to save energy and improve thermal comfort has resulted in a large investment in research into thermal performance of building envelope construction and has been the objective of many studies [2-7]. Palestine suffers from shortage of natural resources, particularly energy, and has diverse climate zones, including hot dry summers and cold winters. The building sector in Palestine represents 64% of national energy consumption and is ranked first before transportation and industrial sectors [8].

Designing a house with energy efficiency design strategies is an essential step to build an energy efficient residential building that can provide thermal comfort to occupants. Optimizing building materials is also an important process that can achieve energy conservation [9]. In order to reduce energy consumption and enhance thermal comfort of occupants in the building sector, it is vital to use building materials with suitable thermal properties [10, 11]. Using heavy thermal mass in building walls is current practice in moderate and hot climates (e.g. Mediterranean climate) as means of



regulating indoor temperature through night-time natural ventilation. While thermal mass controls the amount and rate of heat storage in building components and reduces temperature fluctuations and increases time lag, it does not often preclude the need for using thermal insulation. Two important issues must be dealt with: firstly, means of increasing R-value usually by adding thermal insulation, and secondly, means of increasing thermal energy storage capability typically by increasing thermal mass [12]. In certain climates, massive building envelopes, such as masonry, concrete, earth, and insulating concrete forms can be utilized as one of the simplest ways of reducing building heating and cooling loads. Thermal mass effects occur in buildings containing walls, floors, and ceilings made of logs, heavy masonry, and concrete [1]. Thermal mass can reduce peak cooling loads and indoor air temperature swings in buildings [13]. To reduce indoor air temperature and cooling load peaks, and to transfer the load to a later time in the day, it is possible to store heat in the material of the outer envelope and the interior mass of the building. The energy available from the high solar gains during the day is stored and then is slowly released into the indoor environment at a later time. Thermal mass has also a positive effect on occupant comfort [14]. High mass buildings prohibit high interior air and wall temperature variations and sustain a steadier overall thermal environment [13, 14]. Optimization of thermal mass levels depends on building material properties, building orientation for its location and distribution, thermal insulation, ventilation, climatic conditions and use of auxiliary cooling systems, and occupancy patterns [13]. Effective thermal mass material can absorb and store significant amounts of heat, and this can help to level out temperature variations [15].

A comparative analysis by Kosny et. al. for sixteen different material configurations showed that the most effective wall assembly was the wall with a thermal mass (concrete) applied in good contact with the interior of the building compared with insulation material that was concentrated on the interior side, with the concrete wall core, and insulation placed on both sides of the wall [1]. Materials with high heat capacity and density absorb and store considerable amounts of heat when exposed to an external heat source [15]. The effectiveness of thermal mass in buildings depends on the interactions of several parameters including climatic location, orientation, window area, insulation, ventilation, load profile and occupancy pattern of buildings [13, 1]. Hence, designing to optimize the thermal mass of buildings is a complex issue, and requires careful analysis [16]. Monna et. al. 2016 [17] found that for modern residential buildings in a hot summer and cold winter region, energy demands for heating and cooling may be reduced by up to 60% applying sensitivity analysis which included: improving envelope insulation, using the natural ventilation and shading strategy. The same studies found that buildings insulation has the highest impact on reducing energy consumption, followed by the U-value of windows and shading strategies.

In response to the growing concerns about energy efficiency in buildings and its implications for the user comfort, the research authors are concerned with a variety of factors relating to thermal performance of residential buildings in Palestine. In this context, a particularly interesting aspect is the effect of thermal mass on thermal performance of buildings. The main objective of this research is to assess the effects of thermal mass and insulation's position within the building envelope on indoor thermal environment, which will reflect on potential energy consumption for heating and cooling.

2. Methodology

In Palestine the most used external wall is composed of stone, concrete, hollow concrete block and internal cement plaster, while the concrete flat roof/floor is the most used. More than 70% of residential buildings in Palestinian cities use this kind of external walls and roofs [8]. Those external walls and roofs can contain a high thermal mass due to the high density, specific heat capacity and thickness, as can be seen in Table 1, which will store the heat and emit it in the evening and at night in summer. In winter, this thermal mass will need much more energy to heat, especially in the absence of thermal insulation, beside its high thermal conductivity.

In order to achieve the objective of this study, the investigations were carried out using a simulation model, developed in the DesignBuilder v6 software, for a representative residential building as this is the largest building sector in the region [8]. The representative model was evaluated

under two different climatic conditions; Zone 1 (Jericho city), which is characterized by its hot dry summer and warm winter, and Zone 4 (Nablus city), which is characterized by cold winter, relatively low precipitations and relatively high temperatures in summer, for the following scenarios:

Scenario-1 (Sc-1): Uninsulated envelope with high thermal mass (base case)

Scenario-2 (Sc-2): Insulated envelope with high thermal mass (outside insulation)

Scenario-3 (Sc-3): Insulated envelope with moderate thermal mass (insulation in the middle)

Scenario-4 (Sc-4): Insulated model with small thermal (inside insulation)

Thermal mass is equivalent to heat capacity Q, which is the ability of a body to store thermal energy. It is typically referred to by the symbol Cth and its SI unit is J/°C or J/K and equals.

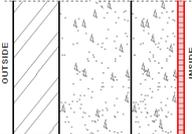
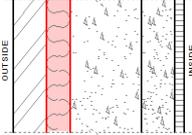
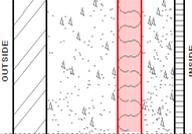
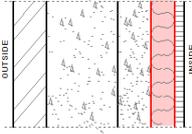
$$Q = C t h \Delta T \dots\dots\dots (1)$$

The most important factor to understand the behaviour of thermal mass is the Thermal Time Constant TTC (τ) for the building envelope, which is defined as the product of heat capacity (Q) and resistance to heat transmission (R).TTC is representative of the effective thermal capacity of a building, where a high TTC indicates a high thermal inertia of the building when a building is affected mostly by heat flow across the opaque parts of the envelope. TTC of an area (A) has been calculated by multiplying the heat capacity per unit area (Q) by the resistance R to heat flow of that area.

$$\tau A = Q R \dots\dots\dots (2)$$

TTCs for each surface are the product of TTCA multiplied by the area. Glazed areas are assumed to have a TTC of 0. Total TTC of the building envelope has been calculated by dividing the sum of all TTCs by the total envelope area, including the glazing areas as seen in Table 1.

Table 1. External walls thermo-physical parameters, and the calculated thermal time constant.

Scenario-1	Wall layers from outside to inside	Density (kg/m ³)	Specific Heat (J/kg·K)	Conductivity (W/m·K)	Thickness (m)	Thermal Time Constant
	Natural Stone	2350	920	1.5 - 2.6	0.07	-
	Reinforced concrete or backfill concrete	2300	670	0.8	0.13	
	Hollow block	1200	840	1.35	0.1	
	Cement Plaster	900	1000	0.21	0.02	
Scenario-2						
	Natural Stone	2350	920	1.5 - 2.6	0.07	40.57
	Polystyrene foam	38	1130	0.033	0.05	
	Reinforced concrete or backfill concrete	2300	670	0.8	0.13	
	Hollow block	1200	840	1.35	0.1	
	Cement Plaster	900	1000	0.21	0.02	
Scenario-3						
	Natural Stone	2350	920	1.5 - 2.6	0.07	17.20
	Reinforced concrete or backfill concrete	2300	670	0.8	0.13	
	Polystyrene foam	38	1130	0.033	0.05	
	Hollow block	1200	840	1.35	0.1	
	Cement Plaster	900	1000	0.21	0.02	
Scenario-4						
	Natural Stone	2350	920	1.5 - 2.6	0.07	7.80
	Reinforced concrete or backfill concrete	2300	670	0.8	0.13	
	Hollow block	1200	840	1.35	0.1	
	Polystyrene foam	38	1130	0.033	0.05	
	Cement Plaster	900	1000	0.21	0.02	

The analysis focuses on typical building apartments of three bedrooms as it represents the majority of apartment buildings in this region [18, 19]. The Building consists of a parking floor and five floors of residential apartments. Each floor has an area of 675 m² distributed into four apartments, staircase and an elevator as can be seen in Figure 1. Physical characteristics of walls and building construction, including the materials of the envelope and glazing ratio are based on on-site studies. Occupancy was five persons by apartment (average family size in Palestine). Hourly simulation was performed for two representative weeks in summer and in winter. Set point temperature is 20°C for winter and 26°C in summer and ventilation rate is 0.0038 m³/s /person, according to ASHRAE standards. Window wall ratio for north façade is 0.4 and south is 0.45 and window shading coefficient 0.719.

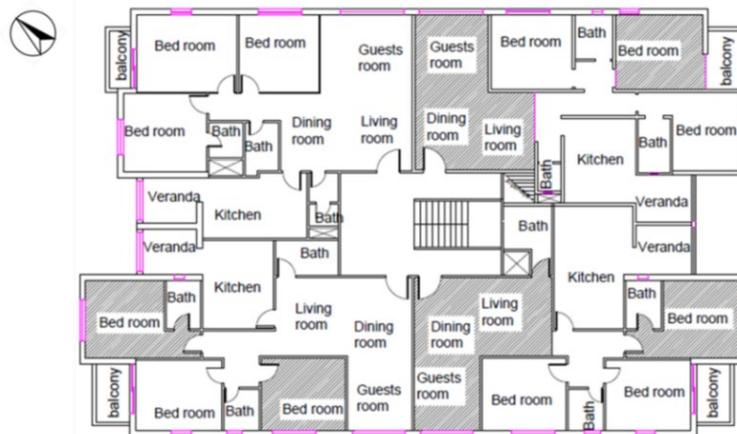


Figure 1. Multi story apartment building, where emphasized areas show the rooms assessed on each floor

3. Results and Discussion

Simulations were performed for six rooms on each floor of the building for different orientations. When no heating or cooling is used, the obtained results for all rooms show similar effects for insulation position and thermal mass on indoor air temperature. Hence, the discussion of the results is limited for the south facing space. Figure 2 illustrates the results of the indoor and outdoor air temperatures during the summer and winter periods for two different climate zones (zone one represented by Jericho city and Zone 4 represented by Nablus city). The results show the effects of thermal mass on the indoor air temperature for insulated and uninsulated external walls for the presented scenarios. It is noticeable that, during the summer period in climate Zone 4, the best performance is for external walls with thermal insulation from the outside (Scenario 2), followed by that of the uninsulated wall (Scenario 1), then the walls with thermal insulation in the middle of the wall (Scenario 3) and the worst performance was for the walls with thermal insulation from the inside (Scenario 4). In Climate Zone 1 the best performance was again for Scenario 2, then followed by Scenarios 3 and 1 respectively and the worst performance was for Scenario 4. Results show that the walls with a high thermal time constant TTC perform better than the walls with low TTC for both climates. It can take the advantage of diurnal changes by storing energy and delaying the effect of temperature variation. However, for low and medium thermal mass there is a difference in thermal performance in different climates.

Results for the winter period show that the best performance was for the walls with insulation from the outside (Scenario 2) and the worst performance was for the walls without thermal insulation (Scenario 1) for both climatic zones. Walls with low thermal mass (insulation from inside - Scenario 4) have a higher indoor air temperature fluctuation, which means they show better performance than Scenario 3 during the day but not during the night. It is noticeable that with multilayer wall constructions, internal temperature fluctuations are subject primarily to material characteristics in the layers next to the internal surface. Therefore, when lining the external walls with insulation on the internal surface (i.e. Scenarios 3 & 4), the insulation layer prevents the variable heat energy in the

space from getting into the heavyweight layer, and as a result, the heavyweight layer tends to have a relatively small damping effect.

Days	summer					winter					
	outdoor Temp.	Sc1	Sc2	Sc3	Sc4	outdoor Temp.	Sc1	Sc2	Sc3	Sc4	
Nablus	1	26.3	28.0	24.5	28.1	28.8	8.7	12.0	18.2	13.8	12.7
	2	26.9	28.1	24.0	28.5	27.9	9.7	11.7	17.8	13.7	12.7
	3	26.2	28.0	24.2	28.5	27.5	8.9	12.0	17.6	13.8	12.3
	4	24.9	27.2	25.1	28.4	28.4	7.6	11.8	17.4	13.6	12.1
	5	26.6	27.2	25.0	28.3	29.6	7.3	11.3	17.1	13.4	12.6
	6	27.3	27.5	25.2	28.8	29.9	7.9	11.1	16.9	13.3	13.4
	7	30.4	28.5	25.6	29.2	30.0	6.1	10.8	16.6	12.9	12.8
	8	31.5	28.9	25.1	29.6	29.3	7.3	10.6	16.3	12.8	13.0
	9	30.5	29.4	24.8	29.8	29.3	7.3	10.6	16.2	12.8	12.9
	10	25.8	29.8	25.0	30.0	29.6	8.5	10.6	16.1	12.8	12.6
	11	24.1	29.0	25.1	29.7	30.0	7.7	10.8	16.0	12.8	12.7
	12	24.8	28.0	26.0	29.6	30.4	8.5	10.7	15.9	12.8	12.8
	13	25.7	28.8	26.5	29.8	30.6	11.7	11.3	16.1	13.4	13.1
	14	26.4	29.3	26.3	30.2	30.5	8.2	11.7	16.1	13.4	13.3
	15	27.7	29.6	26.0	30.2	30.6	8.7	11.3	16.0	13.3	13.0
Jericho	1	32.4	30.5	25.4	28.7	31.5	16.5	17.6	22.2	19.7	21.8
	2	30.9	30.3	25.6	28.7	30.8	18.9	18.1	22.7	20.3	20.8
	3	30.1	29.6	25.7	28.3	29.9	17.4	18.4	22.9	20.6	20.2
	4	30.7	29.4	25.9	28.1	29.5	17.6	18.1	23.1	20.3	19.8
	5	34.6	30.0	26.2	28.6	30.4	18.5	18.1	23.3	20.2	20.4
	6	35.4	31.2	26.7	29.4	31.6	19.6	18.5	23.6	20.5	21.6
	7	33.8	31.6	27.0	29.8	31.9	14.6	18.1	22.1	20.1	17.1
	8	32.9	31.6	27.2	30.0	32.0	14.0	17.0	21.8	19.0	17.0
	9	32.6	31.5	27.4	29.9	31.3	14.0	16.3	21.6	18.4	16.4
	10	31.7	31.1	27.4	29.6	31.3	14.3	15.9	21.6	18.2	16.2
	11	33.8	31.3	27.6	29.7	31.6	13.3	15.9	21.6	18.5	16.6
	12	33.5	31.5	27.8	29.8	32.0	13.6	15.5	21.4	18.0	17.0
	13	34.6	31.6	28.0	30.1	32.4	13.7	15.1	21.4	17.7	17.3
	14	34.0	31.9	28.2	30.3	32.6	14.2	15.3	21.5	18.2	17.6
	15	33.2	31.9	28.2	30.2	32.5	13.2	15.7	21.6	18.6	17.5
		hot				23		cold			

Figure 2. Indoor and outdoor air temperatures (°C) for the four different scenarios in two climatic zones.

4. Conclusion

The paper analyzed the effects of thermal mass in external walls in residential buildings on the indoor thermal performance for different scenarios in two climatic zones in Palestine. The external wall with high thermal insulation (outside thermal insulation) showed the best effect on thermal performance of the building for both climatic contexts in winter and in summer. The uninsulated walls showed the worst effects on building thermal performance in winter in both climatic zones; however, in summer uninsulated walls have slightly better effects than walls with medium and low thermal mass in Climatic Zone 4 and slightly better performance than the walls with low thermal mass in Zone 1.

As a general tendency it can be noticed that for different climate zones in Palestine, lower amounts of thermal mass at the inside of the space (i.e. outer side of thermal insulation) appear to be detrimental in terms of thermal performance and the potential energy demand. It is expected that buildings without thermal insulation and buildings with inside insulation will consume higher energy for heating and cooling compared with buildings with outside thermal insulation.

It is recommended that future studies should consider different insulation materials and thicknesses. Future studies should also carefully investigate the performance of insulated but lightweight walls under different orientation and Palestinian climatic conditions.

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