Effect of Thermal Mass in the Building Envelope on Building Energy Efficiency-Comparative Study with different Districts in Turkey

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Abstract— One of the main functions of architecture is providing interior comfort conditions for building occupants in addition to organizing and designing spaces by considering the determined conditions. Building envelope is important building component that affect energy efficiency in residential buildings The building envelope component is the building elements that separate the internal and external environment of the building, provide the necessary comfort conditions for the internal environment of the building, and are applied for the control of environmental factors such as heat, light and sound in order to create the interior comfort required by the occupants. One of the main ways to reduce the cooling and heating energy expenditures for providing thermal comfort in buildings is to make the right decisions regarding the building envelope where heat transfer takes place in the building and to control the heat transfer in the building envelope.

In this study, the effect of the thermal mass on the building envelope is evaluated over two regions in different climates but with similar thermal conductivity values according to the standards. In this study, to analyze the energy efficiency of thermal mass computer-based energy simulation tool was used. In the study, heating and cooling energy costs were calculated based on the daily and monthly climate data of 8 different building envelope variations and 2 climate regions. The technical aim of this study is to determine how the effect of to use of thermal mass in the main wall, interior, and exterior cladding materials on the heating and cooling energy demands. One of the main functions of architecture is providing interior comfort conditions for building occupants in addition to organizing and designing spaces by considering the determined conditions.

Index Terms—Building Envelope, Energy Efficiency, Thermal Mass, Climate Design.

I. INTRODUCTION

Reducing the energy consumption of buildings has become vital, taking into consideration the limitation of conventional energy resources and the adverse effects associated with the use of such type of energy on the environment [2]. The majority of such energy consumption is utilized to ensure thermal comfort in buildings through heating and cooling applications [1]. Energy-efficient buildings have emerged as a new approach to encourage using natural resources and reduce the energy requirements to maintain comfortable indoor conditions [3]. Buildings, in this case, are designed, as a prerequisite, to ensure minimum heat gain in summer and heat loss in winter to reduce heating and cooling loads. Therefore, selecting the proper thermal properties of a building envelope plays a major role in determining the energy consumption patterns and comfort conditions in enclosed spaces [4]. As part of the building's envelope, walls account for a significant proportion of heat loss and gain [5]. Almujahid et al. (2013) reported that about one-third of heat loss occurs through walls in the case of un-insulated brick veneer dwellings [6]. Windows are the weakest link in a building envelope for heat gain in the summer and heat loss in the winter. The solar gain entering through a window represents the largest source of heat gain through the greenhouse effect when the radiant heat is trapped inside the building by window glasses [7]. Windows also are responsible for about 25-30% of the heat loss in a building because window glazing is a poor insulator [8]. Therefore, it is critically important to determine the proper wall material and window area when designing buildings.

Depending on the characteristics of the physical environmental factors that are effective outside the building, according to different regions and different periods of the year, it is provided with heating and cooling systems to ensure the interior comfort of the building and %52 of them generate heating and cooling energy to provide sufficient comfort indoors [9].

The building envelope is one of the most critical building components affecting energy efficiency in residential buildings. The building envelope component is the building element that separates the interior and exterior of the building from each other, provides the necessary comfort conditions for the interior of the building, and is also applied for the control of environmental factors such as heat, light, and sound to create the interior comfort required by the users. [10]. Energy efficient design of buildings is possible by designing the building envelope according to the environmental conditions and climate data.

By the Energy Performance regulation applied in terms of energy-efficient building design in Turkey, TS825 (Turkish Standard 825) Thermal Insulation Rules for Buildings is referenced in the design of the building envelope. Although the

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applications in this standard provide the control of heat transfer in the building envelope under constant regime conditions, it does not consider the thermal mass feature, which is effective in passively providing heating and cooling energy costs depending on the dynamic thermal properties of the building envelope under temporary regime conditions. By using the thermal mass feature of the building envelope, it is possible to save on heating and cooling energy costs by considering external environmental factors. [11]

II. METHODOLOGY

In this paper, Istanbul and Diyarbakir regions are determined in order to evaluate the thermal mass effect on building envelope in terms of energy usage and thermal comfort in hot-dry and temperate climate regions in Turkey. The total thermal permeability (U value) of the outer wall of the building envelope, which is determined according to the annual heating and cooling day degrees of the determined cities, according to the TS825 Thermal Insulation Rules for Buildings Standard, was determined as 0.57 kWh/m^2. The climate data of the cities are taken from the global climate database, Meteonorm climate database software, and external climatic data such as daily, monthly, and annual temperature, solar radiation, wind, and air humidity were used in energy and climatic comfort calculations in epw (energy plus weather) format. Energy simulation process is made by the Design Builder program, which uses the Energy Plus energy and thermal comfort software engine is used to analyze the energy efficiency.

Climate data of Istanbul and Diyarbakir regions, where the simulate energy performance and thermal capacity of the building envelope, are given in Figure 1 and Figure 2. The climate zone of Istanbul is located in a temperate and humid climate.Istanbul summer mainly average temperature of 27-30 °C , winter mainly average temperature is between 3-5 °C in winter. [12]

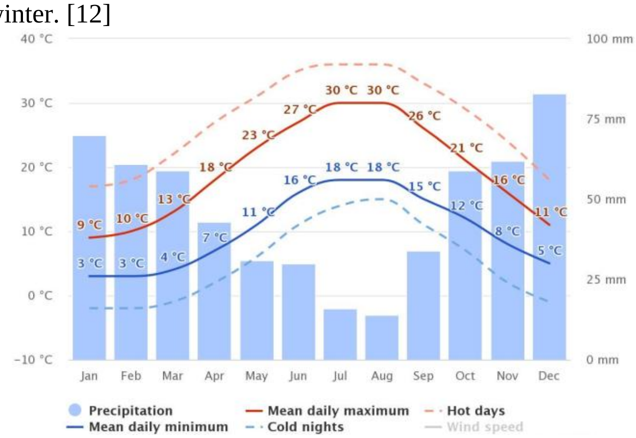


Fig. 1. Average monthly profiles of climatic data for the Istanbul Region.

The climate zone of Diyarbakir is located in a hot and humid climate. Diyarbakir summer mainly average temperature of 34-39 °C, winter mainly average temperature is between 0-1 °C in winter.

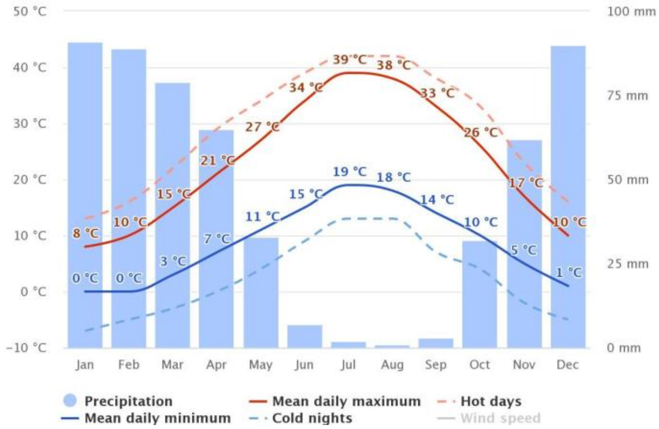


Fig. 2. Average monthly profiles of climatic data for the Diyarbakir Region

In this study, selected building that is a collective housing architectural project is constructed by Housing Development Administration of the Republic of Turkey (TOKİ). The selected building has three floors, and each floor has two flats with an area of 110 m2. The topography of the building is assumed to be inclined. It's assumed that there are no buildings around the building to prevent environmental impacts. The transparency rate of the south façade of the determined building is 19%, the north façade is .16%, and the east and west façades have a transparency rate of .1%. In order to better determine the effect of the thermal mass on the opaque outer walls, the inner walls removed in the energy simulation model of the building, and the outer walls are determined. In the energy simulation model of the building, the floor and ceiling tiles assumed to be impermeable. The plan and energy model images of the building block used are given in Figure 3.

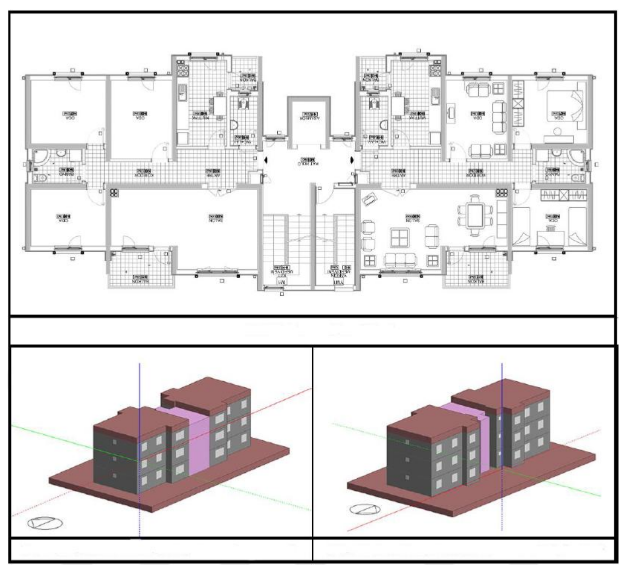


Fig. 3. Plan and Energy Model of Simulated Building.

III. Definition and Calculation of Parameters

The factors affecting the thermal properties of the building envelope and, accordingly, the energy efficiency consist of constant heat flows and dynamic heat flows. The factors that directly affect the heat capacity are the total heat transmission coefficient (U-value), the decrement factor, time lag, and the indoor-outdoor thermal admittance [13].

A. Thermal Conductivity

Thermal conductivity is the value that depends on the amount of heat generated in 1 m^2 area per unit time as a result of the 1 °C temperature difference between the indoor and outdoor air temperatures of a multi-layered structural element that is in contact with the air in the indoor and outdoor environment [14].

$$U_0 = \frac{1}{\frac{1}{a_i} + \frac{d_1}{\lambda_1} + \frac{d_2}{\lambda_2} + \cdots + \frac{d_n}{\lambda_n} + \frac{1}{\alpha_d}} \tag{1}$$

B. Decrement Factor

Decrement factor is the ratio of the temperature amplitude on the inner surface to the temperature amplitude on the outer surface due to periodic thermal movements in the building shell during the day. Decrement factor is the thermal inertia of the building envelope in transmitting the external temperature changes to the interior [15].

$$f = \frac{\mathrm{T}_{i(max)} - \mathrm{T}_{i(avg)}}{\mathrm{T}_{d(max)} - \mathrm{T}_{d(avg)}} \tag{2}$$

C. Time Lag

Time lag or time delay is defined as the time interval that occurs in the sinusoidal temperature wave formed in the structural element in temporary periodic thermal currents, with the effect of the highest equivalent external temperature during the day until the highest temperature formed on the outer surface of the construction element and the highest temperature formed on the inner surface of the construction element. [16].

$$\Phi = t_{y_{i(\max)}} - t_{y_{i(\min)}} \tag{3}$$

D. Internal Thermal Admittence

Thermal admittance is a dynamic quantity related to the ability of a material or structural component to absorb heat and dissipate the absorbed heat during periodic heat flow with the medium. It directly affects the heat storage ability of the material. The thermal admittance value is an important factor affecting the internal and external surface temperatures of a material or building component during periodic heat flow [17].

Interior thermal admittance varies depending on the thermophysical properties of the materials in the inner layer of the building component. [17].

$$Y_{11} = Y_i = \frac{Z_{11}}{Z_{12}} = \frac{q_1}{\theta_1} \tag{4}$$

E. External Thermal Admittence

Exterior thermal admittance varies depending on the thermophysical properties of the materials in the outer layer of the building component. [17].

$$Y_{22} = Y_e = \frac{Z_{22}}{Z_{12}} = \frac{q_2}{\theta_2} \tag{5}$$

IV. Building Components

The exterior wall building envelope alternatives used in this study are divided into two classes as light-weight and high-weight. The main wall material of the lightweight building envelope alternatives is aerated concrete. In high-weight building envelope alternatives, the main wall material is normal aggregate concrete. In addition, to analyze the effect of heat capacity on interior and exterior surfaces on energy efficiency, gypsum-based interior and exterior coating material, which can describe as a light material in building envelope alternatives used. The natural stone covering material is used as interior and exterior covering material, which can describe as heavy.

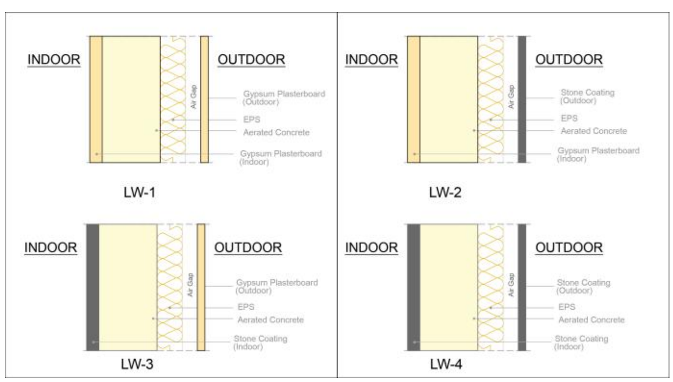


Fig. 4. Lightweight building envelope alternatives.

The thermal properties of light weight building envelope alternatives showing the thermal capacity characteristics are given in Table-I. As the inner and outer cladding materials of the building envelope alternatives get heavier, the time delay factor increases and the amplitude reduction factor decreases.

TABLE I: LIGHTWEIGHT BUILDİNG ENVELOPE ALTERNATİVES

	Thermal Conductivity	Time Lag	Decrement Factor	Internal Thermal Admittance	External Thermal Admittance
Unit/ Wall Alt.	U W/m²K	φ h	f -	Y_{11} W/m²K	Y_{22} W/m²K
LW-1	0.57	7.45	0.410	2.10	1.57
LW-2	0.57	7.77	0.405	2.10	4.95
LW-3	0.57	8.20	0.400	3.98	1.57
LW-4	0.57	8.57	0.394	3.98	4.95

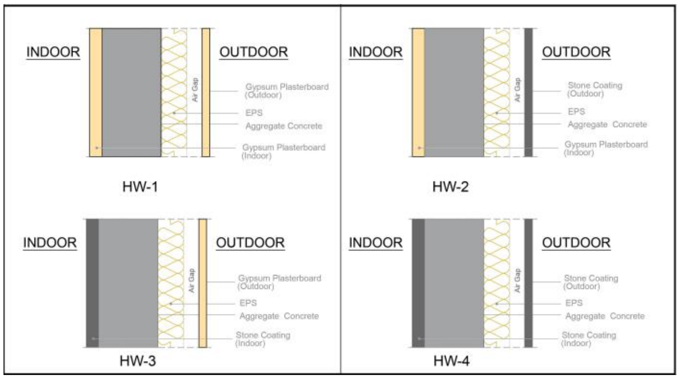


Fig. 4. Heavyweight building envelope alternatives.

The thermal properties of heavyweight building envelope alternatives showing the thermal capacity characteristics are given in Table II. It is seen that the time delay factor increases, and the amplitude reduction factor decreases with the weighting of the interior and exterior coating material of the building shell alternatives. Heavyweight building envelope alternatives have more time delay factors than lightweight building envelope alternatives. The values showing the heat capacity of the heavyweight building envelope alternatives are higher..

TABLE II: LIGHTWEIGHT BUILDİNG ENVELOPE ALTERNATİVES

	Thermal Conductivity	Time Lag	Decrement Factor	Internal Thermal Admittance	External Thermal Admittance
Unit/ Wall Alt.	U W/m²K	φ h	f -	Y_{11} W/m²K	Y_{22} W/m²K
LW-1	0.57	7.45	0.410	2.10	1.57
LW-2	0.57	7.77	0.405	2.10	4.95
LW-3	0.57	8.20	0.400	3.98	1.57
LW-4	0.57	8.57	0.394	3.98	4.95

It is observed that there is an inversely proportional numerical relationship between the decrement factor and time lag properties. It is seen that as the unit volume weights of the interior and exterior coating materials used in the building envelope increase, the time lag feature increases, and the decrement factor feature decreases.

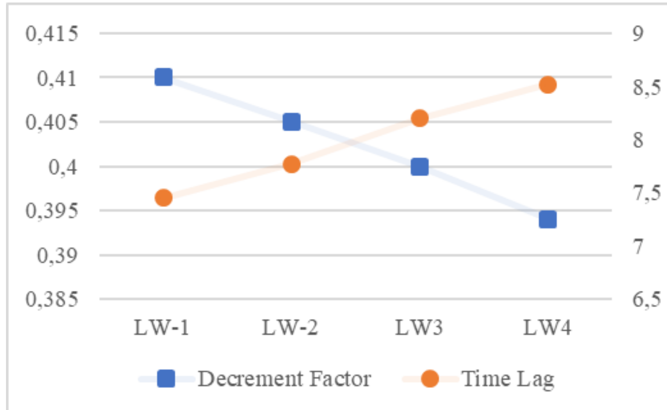


Fig. 5. Light-wight building envelope alternatives.

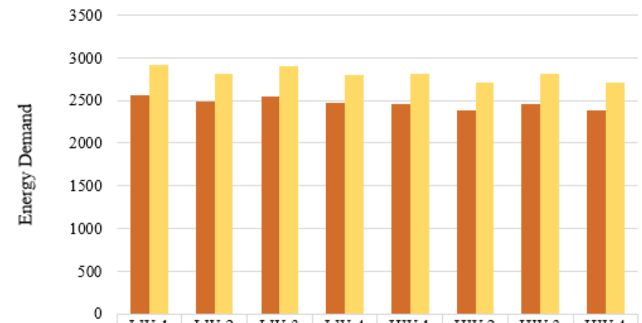
V. Results and Discussions

In order to analyze the effect of the use of the heat capacity feature in the building envelope on the energy efficiency and thermal comfort of the building, building energy simulations of 8 building envelope variations were made in Diyarbakir and Istanbul regions. The data related to energy simulation is given in Table III. In the building energy simulation, the annual heating and cooling energy loads of the building envelope variations were calculated.

TABLE III: BUILDING SIMULATIN DATA

	Type	Unit	Value
Building			
	Net Floor Area	m^2	220
	Net Volume	m^3	3825
	Oriantation	-	South
Activities and Lighting			
	Total Internal Gains	W/m $_2$	18
	Operation Schedule		08:00-19:00
	Heating/Cooling System		08:00-19:00
	Weekly operating system	1w	5/7
Operation			
	Heating set point	°C	20
	Cooling set point	°C	26
	Minimum ventilation rate	vol/h	1.35
	Minimum ventilation fresh air rate	vol/h	0.1
	Night ventilation	vol/h	4

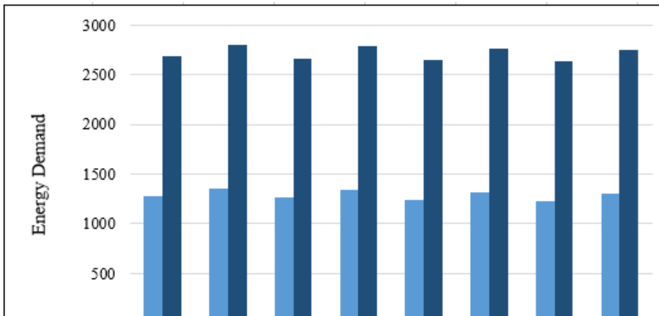
Energy simulation results show that heating energy load analysis results of the building envelope alternatives are examined and the simulated building envelope variation that gives the best results for the Istanbul region is HW-2. For the In Diyarbakir region energy simulation, the HW-4 building envelope alternative, which gives the best performance heating energy load. There is an energy difference of 7-12% between the two climate zones in terms of heating energy load.(Fig. 6)



	LW-1	LW-2	LW-3	LW-4	HW-1	HW-2	HW-3	HW-4
İstanbul	2564,1	2487,1	2549,8	2472,8	2460,7	2383,7	2461,8	2384,8
Diyarbakır	2916,1	2817,1	2900,7	2801,7	2810,5	2708,2	2806,1	2703,8

Fig. 6. Heating Energy Demands

Energy simulation results show that cooling energy load analysis results of the building envelope alternatives are examined and the simulated building envelope variation that gives the best results for the Istanbul region is HW-2. In In Diyarbakir region energy simulation, HW-4 building envelope alternative, which gives the best performance at heating energy load. There is an energy difference of 51-53% between the two climate zones in terms of heating energy load. .(Fig. 7)



	LW-1	LW-2	LW-3	LW-4	HW-1	HW-2	HW-3	HW-4
İstanbul	1281,5	1355,2	1267,2	1339,8	1245,2	1318,9	1233,1	1307,9
Diyarbakır	2682,9	2797,3	2664,2	2780,8	2643,3	2762,1	2629	2747,8

Fig. 7. Cooling Energy Demands

As a result of the analyzes made to determine the effect of thermal mass on building energy consumption, there were differences in energy expenditures in the Istanbul region, which is located in a moderately humid climate zone, and Diyarbakir, which is located in a hot-dry climate region. In the energy load calculations made for the two regions, the difference in the heating energy expenditures of the building envelope variations created a lower difference than the difference in the cooling energy expenditures. In this case, the total thermal transmittance value (u-value) specified in the TS825 standard gave a close result in terms of heating energy expenditures in the winter period, but the energy expenditure differences between the two regions were high in terms of cooling energy expenditure. .(Fig. 8)

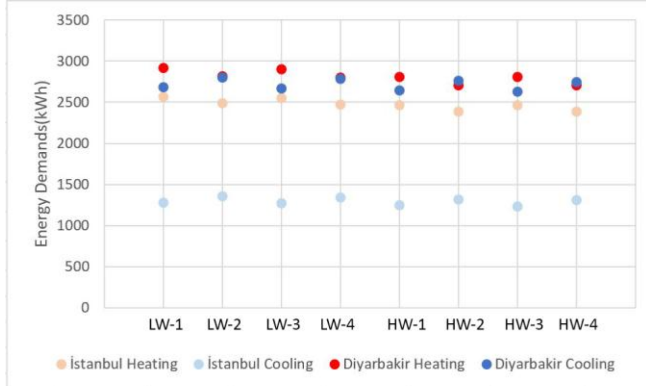


Fig. 8. Heating and Cooling Energy Demands

VI. CONCLUSION

One of the main ways to reduce the cooling and heating energy expenditures for providing thermal comfort in buildings is to make the right decisions regarding the building envelope where heat transfer takes place in the building and to control the heat transfer in the building envelope. In the period when cooling is desired, the amount of heat transfer in the building envelope and the values of the inner surface and indoor air temperatures formed in the indoor environment; such as time lag, decrement factor, indoor and outdoor thermal admittance value, are the results of the dynamic thermal properties of the envelope. Therefore, by keeping the dynamic thermal values of the building envelope under control, it is possible to reduce the cooling energy expenditures and lower the inner surface and indoor air temperature values in the summer period, to reduce the heating energy expenditures in the winter period and to increase the interior surface and indoor air temperature values with the effect of solar radiation.

Building envelope exhibits different thermal behaviors in terms of thermal mass during the heating and cooling periods necessitates an optimization by considering the heating and cooling days of the climate zone in which the building envelope is used. In addition to the limit values of the total heat transmission coefficient (U value) of the building envelope, which is given in the TS 825 "Thermal Insulation Rules for Buildings " standard, which is considered in the design of the building envelope, and which is based only on the shell performance during the heating period, a method that takes into account the dynamic thermal properties of the building should be developed and included in the standard.

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