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Thermal Behavior Analysis of the External Shell of Buildings Constructed with Traditional and Modern Materials and Execution Technologies for Energy Consumption Optimization; Case Study: Residential Buildings in Mashhad City*

Seyed Mehdi Madahi[a]- Mahsa Abbasi[b]**

[a] Assistant Professor of Architecture, Department of Architecture, School of Architecture and Urban Planning, Khavaran Institute of Higher Education, Mashhad, Iran.

[b] M.A. of Architecture, School of Architecture and Urban Planning, Khavaran Institute of Higher Education, Mashhad, Iran (Corresponding Author).

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ABSTRACT

Energy saving is one of the key challenges in the world. In recent years, there have been many concerns about the environmental consequences of energy consumption. In Iran, the building sector accounts for about 40% of total energy consumption. The building shell plays an essential role in controlling environmental conditions as the primary intermediary between the indoor and outdoor. The current study aims to investigate the thermal behavior of external walls of buildings in Mashhad city. The present study is carried out using a combined research and the external walls common in Mashhad city are identified through field studies and then, simulated in Design Builder software. Additionally, several new external walls, which are limited in terms of execution in Mashhad, are studied. The results show that among various external walls common in Mashhad City, HCB1 (a wall with 15cm clay block) is the weakest wall in terms of thermal response and A2 (a wall with 10cm ACC block and polystyrene insulation) is the most optimal wall in terms of thermal energy saving (. Using A2 wall will save 50% of total thermal load and 73% of heat loss through wall. However, the L2 wall (A wall with 10cm Leca block and polystyrene insulation) performs better in cold seasons because it prevents the exit of indoor heat due to its higher admittance coefficient, resulting in less energy required to meet building heating need, compared to other walls. Also, on the implementation of the dry facade system of the walls, it can be seen that implementing dry facade will reduce the total thermal load and heat loss through walls.

Keywords: Thermal Comfort, Energy Saving, External Walls, Building Shell, Mashhad City.

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** E_mail: mahsa.abasi7777@gmail.com

1. INTRODUCTION

The environmental crisis of the last half-century and recent years has posed new challenges to human life on Earth. The consequences of the machine and industrial lifestyles and the increasing use of fossil fuels to achieve greater comfort in everyday life have placed the focus on environmental issues and the optimal use of fuel. In architectural design, thermal comfort is one of the most important issues and providing thermal comfort to residents is one of the main concerns in the design of living spaces. Nowadays, compared to world standards, in Iran, energy consumption in the building sector is at a high level. This high level can be attributed to various factors and issues. In the meantime, the role of external walls and shells should not be overlooked. Energy consumption in buildings accounts for one-third of annual energy consumption in Iran, with heating and cooling contributing the most. Consequently, it is essential to develop some solutions that can reduce energy consumption in this sector. Observing the slightest details can have a great effect on reducing energy consumption in buildings. Consequently, by moderating the building construction and design methods we can achieve the ideal design. As mentioned, it is obligatory to investigate the properties of the external walls to obtain the energy and achieve the optimal pattern. A large part of the retaining members between the inside and outside of the building includes the walls, so if proper materials are used, a lot of energy loss could be prevented. Moreover, energy saving can be significantly improved if proper measures are taken to reduce heat transfer through the outer shell of the building.

2. RESEARCH BACKGROUND

Most research on thermal behavior analysis of buildings shows that one of the most important factors in energy saving is a design in harmony with the environment (Nasrollahi, 2010, p. 7). The external walls of a space (including outer piers, ceilings, openings, etc.) act as a shell-like structure that surrounds inner spaces and separates them from the surrounding environment, this separation is done to achieve a variety of purposes including providing physical and psychological security, controlling climatic factors, defining architectural enclosure, creating privacy, etc. (such purposes influence the formation of inner spaces). The type and kind of the outer shell of the spaces play an essential role in achieving these goals (Pourdeyhimi & Gosili, 2015, p. 59). Building a shell as a major mediator between inner and outer spaces plays a significant role in reducing cooling and heating loads. The amount of energy savings through the building shell depends on several factors, including the materials, openings, thermal mass, thermal insulation, etc. (Shaghayegh, 2013, p. 152). Using thermal insulation in walls is one of the effective ways to reduce the thermal and cooling loads of a building (Omidvar & Rati, 2013, p. 154). Studies show that for any amount of thermal mass, the thermal performance becomes better as the mass approaches the inner surface and the insulation approaches the exterior (Al-Sanea, Zedan, & Al-Hussain, 2012, p. 123). The optimum insulation thickness depends on the degree of daytime temperatures and the overall thermal resistance of the wall (Aste, Angelott, & Buzzetti, 2009, p. 117). In a study where the optimum thickness of the insulation was calculated based on the delay time and the reduction factor under steady-state conditions using Finite Difference Method, the results showed that the northern walls require the least amount of insulation, while the eastern and western walls need the thickest insulation. Based on the results of this research, wall structure can be optimized considering the orientation of different walls, based on the balance between the cost of insulation and the cost of energy consumption (Ozel, 2011, p. 3857). Also, about the application of colors to the facade, using brighter colors on the exterior surfaces of the building will effectively reduce the temperature fluctuations inside the building (Cheng, 2005, p. 531).

3. RESEARCH QUESTIONS

Since energy saving is very important at present, this study has attempted to answer the following questions to minimize energy loss in the building sector.

1. What factors influence the thermal behavior of external walls of residential buildings in Mashhad City to reduce energy consumption?
2. Which materials, among the common materials used in external walls of residential buildings in Mashhad, are most suitable for saving on thermal energy consumption?

4. METHOD

This research is applied, descriptive-analytical research which was carried out on residential building in Mashhad City, using descriptive, analytical and simulation methods and logical reasoning at different research stages. In the present study, the required data were collected by second desk study and field study. In the present study, the analysis of existing external walls in Mashhad and the implementation of new dry façade system will be carried out using Design Builder software as follows: the building is first simulated by Design Builder software and the required heating and cooling energies are estimated, then the external walls of the sample are simulated in the software and the thermal properties of the materials are given to the software. Each material is individually simulated monthly and yearly, and ultimately all materials are compared in terms of energy. Materials are different in thermal conductivity, heat resistance, density, and diffusion coefficient, so the American Ashrae Standard, which calculates and measures the thermal coefficients of various materials, is used. These coefficients are used in the Design Builder software, with Plus Energy motor, to calculate the thermal performance and to measure the annual and monthly cooling and heating load consumption. This software works as follows: first, using drawing commands, the desired building is plotted, then the thermal load is calculated by determining the materials of walls and windows, the installation system, the building use, etc. It is important to determine the building use because the buildings have different usage hours depending on their use.

5. CONCEPTS AND DEFINITIONS

The important concepts and definitions used in this research are as follows.

5.1. Cooling Degree Day

It is a unit based on temperature and time, which is used to estimate the energy consumption and to determine the cooling load of a building in hot weather. A cooling degree day is equal to the sum of the difference between average daily temperature and 21, at times when the average daily temperature is above 21 ºC (Topic 19 National Building Regulations, 2013, p. 56).

5.2. Heating Degree Day

It is a unit based on temperature and time, which is used to estimate the energy consumption and to determine the heating load of a building in cold weather. A cooling degree day is equal to the sum of the difference between average daily temperature and 18 ºC, at times when the average daily temperature is below 18 ºC (Topic 19 National Building Regulations, 2013, p. 56).

5.3. Thermodynamic Properties

Applying steady-state calculations (which lead to the thermal conductivity of the materials) alone is not appropriate for evaluating the thermal performance of materials, for example, two walls with the same thermal conductivity coefficient can absorb and reflect heat in different amounts and ways (McMullan, 2007, p. 14). In fact, due to properties such as thermal capacity, density, and thermal conductivity of materials and variable climatic conditions, the materials exhibit dynamic behavior that is not included in the steady-state calculation. In steady-state calculations, to calculate the thermal conductivity, the temperatures of the two sides of a wall or any structure studied are considered constant, while in reality, the building shell is exposed to varying temperatures during the day.

5.4. Admittance Procedure and Analysis of Effective Parameters in It

Numerous methods have been introduced to study the thermal behavior of materials under variable environmental conditions, as a result, various parameters have been defined to consider the effect of thermal mass in thermal behavior studies (Balaras, 1996, p. 7). According to admittance procedure, it is necessary to consider the parameters such as the admittance coefficient, reduction coefficient and the surface coefficient, in addition to the thermal conductivity coefficient, in calculation (CIBSE, 2006, p. 5).

5.5. Admittance Coefficient

This coefficient describes the ability of a material to transmit heat to the environment for any degree of the temperature difference between the environment and that material (CIBSE, 2006, p. 6). The parameters involved in the definition of this variable are thermal capacity, density, thermal conductivity, surface resistance, and possible duration for the material to be absorbed and released by the material, which is normally considered 24 hours. Higher values of admittance coefficient imply less fluctuations of internal temperature, thus, from a thermal mass point of view, unlike thermal conductivity, higher admittance is more favorable. For a clearer distinction between the thermal conductivity coefficient and the admittance coefficient, it should be noted that two different structures with the same heat insulation capability can exhibit different behavioral characteristics in terms of interacting with ambient heat and moderating indoor air temperature fluctuations (Shaghayegh, 2013, p. 74).

5.6. Experimental Model

To investigate the thermal performance of external walls to optimize the energy consumption, a four-story building, whose first floor has two residential units and built on a pilot, was designed as an example of residential apartments in Mashhad City and then, simulated in Building Design software. By analyzing the walls of this building, the researchers have tried to offer appropriate patterns for reducing energy dissipation through the external walls of buildings in Mashhad City. According to statistics obtained from Strategic Research and Studies Management Office, affiliated to Mashhad Municipality, 82.6 percent of residential buildings in this city have medium density (3 floors above the pilot) or high density (4 floors above the pilot), and according the City Council approval, it is possible to purchase an additional floor, in addition to the number of floors determined in the building permission, under natural conditions, so the average number of floors of buildings in Mashhad City is four floors above the pilot. That is why in this study, higher number of floors (4 floors above the pilot) is considered to see the greatest impact. Moreover, according to information obtained from the website of Mashhad Municipality (esup), Khazani detailed plan, adopted in 1980, includes the highest frequency of residential buildings in Mashhad, so the

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case study was considered within the limit of this plan. So, according to the published architectural and urban planning rules, this detailed plan was divided into three residential zones including Zone 1, Zone 2 and zone 3 and various density and floor area ratio rules were assigned to each region. Zone 2 has the highest frequency of residential building, that is why, a land of 300 m^2 area (most of the lands in the area are of 250 to 300 square meters) and high density (the frequent density in Mashhad) is considered. The floor area ratio in this area is 60%. Also, the number of units allowed is obtained by dividing the building site (i.e. land area) by the minimum land area for each residential unit, and in Zone 2, the minimum land area with a high density is 62.5 m^2. Thus by dividing 300 by 62.5, the number of units is 4.8~5. so, the sample building has 5 units on 4 floors, with a floor area of 180 m^2. Considering 20 m^2 building common area per floor, three 160-m^2 units on the ^{2}nd to ^{4}th floors and two 80-m^2 units on the first floor are considered.

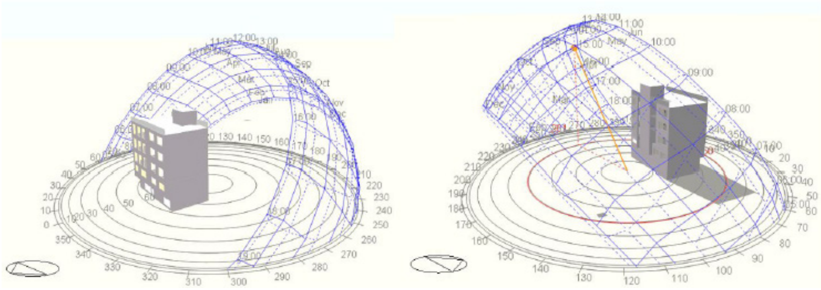


Fig. 1. Schematic Drawing of the Sample Space

6. RESEARCH PARAMETERS

In the current study, the thermal mass of the shell is considered as the main parameter with the highest influence on the thermal behavior of the building. Table 2 shows the details of six typical walls used in the outer shell of apartments in Mashhad, and Table 3 presents three dry facades proposed in the study and their thermal behavior is examined to determine their thermal performance. The investigation consists of two parts. 1-Examination of thermal performance of walls without considering cooling and heating systems: At this stage, the thermal behavior of the mentioned structure under unstable conditions and its effect on indoor temperature are investigated using the Admittance procedure. To investigate the effect of the Admittance coefficient on thermal performance, it is necessary to perform simulation under unstable conditions and compare it with stable conditions. Therefore, in addition to the annual thermal performance, the thermal performance of the sample wall structures is investigated in the coldest week of the year (i.e. from 13 January to 19 January), as relatively stable conditions, and the hottest week of the year (i.e. from 20 July to 26 July), as relatively unstable conditions. 2- The thermal performance of the sample walls is investigated by considering the heating and cooling systems and the structures are compared with each other in heating and cooling energy savings.

7. SIMULATION SCENARIO

To analyze and evaluate the external walls of building, a project was considered as a sample with the following characteristic in Mashhad Cit.

7.1. Location

The sample space is located in Mashhad City at 36.20º North latitude and 59.35º East longitude, and 999 m above sea level. The climatic data used is based on Ashrae weather data.

7.2. Activities

The sample space has air conditioning system within the thermal comfort limit. Since the study focuses on residential spaces, the residential areas part was selected in the software and the default time schedule and number of individuals determined for residential area in the software were considered. In this simulation, all the factors affecting the pure thermal behavior of the building shell such as indoor heat-generating sources (electric appliances, stove and oven, and other heat-generating appliances) have been excluded. In the first stage, the heating and cooling systems were not introduced and included in the simulation to assess the pure behavior of the building shell's energy system when exposed to changing climatic conditions. In the second stage, to evaluate energy consumption, heating and cooling systems were considered on and the simulation data were compared with each other to obtain optimal systems for reducing energy consumption. Comfort temperature was set to 20 and 24.5 for heating and cooling, respectively. These numbers are selected based on the following thermal comfort table.

Table 1. Thermal Comfort Range

-	DEC	NOV	OCT	MAR	FEB	JAN	Mean
The Lower Limit of Comfort	17.509	19.247	21.227	18.5095	17.308	16.645	18.4078
Optimal Conditions	19.259	20.997	22.977	20.2595	19.058	18.395	20.1578
The Upper Limit of Comfort	21.009	22.745	24.727	22.0095	20.808	20.145	21.9078
-	**SEP**	**AUG**	**JUY**	**JUN**	**MAY**	**APR**	**Mean**
The Lower Limit of Comfort	22.471	24.0205	24.2185	23.4325	22.0375	20.155	22.7225
Optimal Conditions	24.221	25.7705	25.9685	25.1825	23.7875	21.905	24.4725
The Upper Limit of Comfort	25.971	27.5205	27.7185	26.9325	25.5375	23.655	26.2225

(Sabeti, 2014, p.17)

7.3. Openings

Under this subtitle, the settings of openings are done. The windows are of thermally broken aluminum double glazed windows with 4mm-thick ordinary glass in gold color and the gas trapped between the glasses is 13mm-thick argon. Before the popularity of UPVC windows, aluminum windows were widely used. The main problem with aluminum is its conductivity. Thermally broken frames have been introduced to solve this problem. The Thermal Break System consist of two separate aluminum profiles that are joined by polyamide blades. Polyamide blades prevent heat transfer from the surface to surface, thermal bridge and loss of energy. Aluminum has higher stability and flexural strength than UPVC. It is resistant to fire, regarded as a capital product and can be recycled. To reduce single-glazed window problems, double-glazed windows with a layer of air between glasses. This reduces the glass heat transfer coefficient from 2.3 °w/m^{2}c to 6 °w/m^{2}c. The type of gas contained between the glasses is also effective in transmitting heat. The use of inert gases such as krypton and argon between glasses reduces the heat transfer coefficient by approximately 10% (Namazian, Sepehri, 2016, p. 94). For these reasons in this study, a frame was chosen for the thermally broken aluminum double glazed windows.

7.4. Cooling and Heating System

As mentioned above, in the first stage, the heating and cooling systems are considered as switched off, and in the second stage, using the heating and cooling system, the heating and cooling energy consumption of the sample walls are investigated. The considered type of system was Fan coil unit. The fuel of the heating and cooling system was considered natural gas. Cooling and heating systems were used to simulate the space temperature to the comfort temperature of 20 for summer and 24.5 for winter. The schedule for powering the heating system on and off was set using Mashhad weather data and taking into account the hours of space usage for a residential environment. Software uses Mashhad weather data and the times residential areas require to use cooling and heating systems, to achieve thermal comfort in the calculations.

7.5. Structures

In this study, since the purpose of this study was to investigate the effect of type and thickness of materials on the thermal performance of external walls, the materials used in the simulation for ceiling and floor structures as well as windows were considered identical in in all models and only the external wall material was changed. Since observation of Topic 19 of National Building Regulations for the buildings of groups (b, c, d) in Mashhad City was enforced by the Construction Engineering Organization, all builders are required to meet the minimum requirements in their execution project.

The internal floor is of composite that on the lower floor, it is covered with plaster and on the upper floor with ceramic.

The internal floor attached to the pilot is of composite that on the lower floor it is covered with plaster and on the upper floor with ceramic and a 5-cm-thick thermal insulation (polystyrene) is also used.

Flat Roof detail is of composite type that on the lower floor, it is covered with plaster and on the upper floor with stone, and a 5-cm-thick thermal insulation (polystyrene) and a moisture insulation (bituminous waterproofing and bitumen) have also been used.

Ground Floor includes foundation, blockage, gravel, lean concrete, cement, and rock mortar.

The interior partitions are plastered with 15cm clay on both sides.

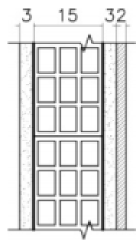
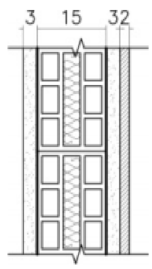
Also, through field studies, observations and referrals to the Association of Mass Producers and the Association of Contractors and Construction Executives, all materials used in the outer shell of residential buildings in Mashhad are identified and listed in Table 2.

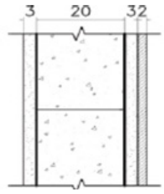
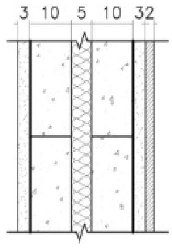
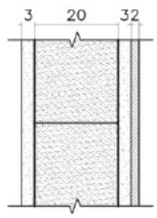
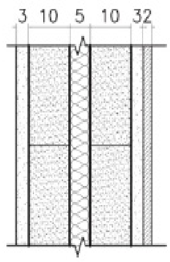
According to this table showing the frequency percentage of materials used in external walls of residential buildings in Mashhad, and national building regulations including topics 18, 5 and 19 that discuss the insulation and sound regulation, building style and energy saving, those materials which are more common in Mashhad City and meet the basic standards of national building regulations have been studied.

Table 2. List of Materials Used for the External Walls of Residential Buildings in Mashhad City

Materials Used for External Walls of Residential Buildings in Mashhad City	Frequency (%)	Materials Used for External Walls of Residential Buildings in Mashhad City	Frequency (%)
11cm pressed brick wall with 4cm plaster, soil and 4cm plaster, and 5cm sand and cement mortar.	6 %	Clay block walls with a thickness of 15 cm, 4 cm thick plaster-soil, and cement sand mortar and stone with a thickness of 5 cm.	15%
22cm pressured brick wall with 4cm plaster, soil and 4cm plaster, and 5cm sand and cement mortar.	7%	Wall with 20 cm thick Leca block, 4 cm plaster and soil plaster and 5 cm thick cement and stone mortar.	14%
10cm clay brick wall with 4cm plaster, soil and 4 cm plaster thickness, and 5cm thick cement and rock mortar	5%	Clay block Wall and polystyrene insulation 15 cm thick, plaster and soil and plaster 4 cm thick, and cement sand and stone mortar 5 cm thick	6%
7.5cm concrete wall with 4cm plaster, soil and plaster thickness, and 5cm cement and rock sand mortar	3%	Wall with Leca block and 25 cm thick polystyrene insulation, 4 cm thick plaster and soil plaster, and 5 cm thick cement and stone mortar.	7%
Wall with a 10cm thick lean concrete block with plaster and soil and 4cm plaster, and 5cm sand and cement mortar.	4%	Wall with Hoblex block 20 cm thick, plaster and soil and plaster 4 cm thick, and cement sand and stone mortar 5 cm thick	17 %
Wall with 25cm thick insulating concrete form (ICF) structure filled with reinforced concrete, 4 cm thick plaster and soil plaster, and 5 cm thick cement and stone mortar.	2%	Wall with Hoblex block and polystyrene insulation 25 cm thick, plaster and soil and plaster 4 cm thick, and cement sand and stone mortar 5 cm thick	8%
Wall with Hoblex block and polystyrene insulation 25 cm thick, plaster and soil and plaster 4 cm thick, and cement sand and stone mortar 5 cm thick	3%	Other walls	3%

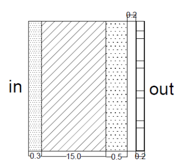
Table 3. Thermo-physical Properties of Materials Used in Six Sample Walls common in Mashhad City

Materials From the Inside to Outside	Thermal Conductivity (w/mk)	Heat Capacity (J/kg-k)	Density (kg/m3)	Thickness (m)	Wall Type	Details
Gypsum-soil and gypsum mortar	0.4	1000	1000	0.03	Hollow clay block HCB1 15	
Clay block	0.5	840	1300	0.15		
Sandstone cement mortar	0.72	780	1860	0.03		
Façade stone (Travertine)	1.4	950	2000	0.02		
Gypsum-soil and gypsum mortar	0.4	1000	1000	0.03	HCB2 ceramic block with insulation	
Clay block	0.5	840	1300	0.065		
Polystyrene insulation	0.033	1200	30	0.02		
Expanded clay block	0.5	840	1300	0.065		
Cement sand mortar	0.72	780	1860	0.03		
Façade stone (Travertine)	1.4	950	2000	0.02		

Materials From the Inside to Outside	Thermal Conductivity (w/mk)	Heat capacity (J/kg-k)	Density (kg/m3)	Thickness (m)	Wall Type	Details
Gypsum-soil and gypsum mortar	0.4	1000	1000	0.03	L1 s	
Leca 20 block	0.23	1000	900	0.20		
Cement sand mortar	0.72	780	1860	0.03		
Façade stone (Travertine)	1.4	950	2000	0.02		
Gypsum-soil and gypsum mortar	0.4	1000	1000	0.03	L2 block Leka 10 with insulation	
Leca 10 block	0.23	1000	900	0.10		
Expanded Polystyrene Insulation	0.033	1200	30	0.05		
Leka Block 10	0.23	1000	900	0.10		
Sand Mortar	0.72	780	2000	0.03		
Façade stone (Travertine)	1.4	950	2000	0.02		
Gypsum-soil and gypsum mortar	0.4	1000	1000	0.03	A1 ACC block 20	
AAC 20 block	0.17	700	1000	0.20		
Cement sand mortar	0.72	780	1860	0.03		
Façade stone (Travertine)	1.4	950	2000	0.02		
Gypsum-soil and gypsum mortar	0.4	1000	1000	0.03	A2 block ACC 10 with insulation	
Block AAC 10	0.17	700	1000	0.10		
expanded polystyrene insulation	0.033	1200	30	0.05		
block AAC 10	0.17	840	1000	0.10		
Cement sand mortar	0.72	700	1860	0.03		
Façade stone (Travertine)	1.4	950	2000	0.02		

Other external walls investigated in this study are the dry stone facade with three sample materials of Leca blocks, clay and ACC blocks. Dry façade with a circulating airflow pattern is a building system that has been widely used in recent decades in most countries due to the optimization of energy consumption. The system consists of exterior insulation, an insulation layer attached to the retaining structure, and a facade layer attached to the building using a suitable connection system. Between the insulation layer and the facade, there is a gap for air. This gap creates a "stack phenomenon", resulting in the creation of effective natural airflow, with significant advantages, for the whole system, and thereby, preventing energy dissipation.

Table 4. Thermo-Physical Properties of Materials Used In Three Types of Walls with Dry Facade

Materials From the Inside to Outside	Thermal Conductivity (w/mk)	Heat apacity (J/kg-k)	Density (kg/m³)	Thickness (m)	Wall Type	Details
Gypsum-soil and gypsum mortar	0.4	1000	1000	0.03	Dry implementation of 15 cm hollow clay block	
clay block	0.5	840	1300	0.15		
polystyrene insulation	0.033	1200	30	0.05		
Air layer	0.3	1000	1000	0.025		
Façade stone (travertine)	1.4	950	2000	0.02		

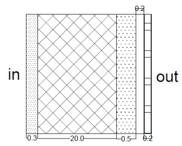
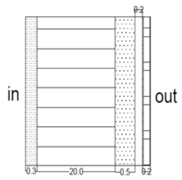
Materials From the Inside to Outside	Thermal Conductivity (w/mk)	Heat apacity (J/kg-k)	Density (kg/m³)	Thickness (m)	Wall Type	Details
Gypsum-soil and gypsum mortar	0.4	1000	1000	0.03	Dry execution of 20 cm Leca block	
Leca block	0.23	1000	900	0.20		
Polystyrene insulation	0.033	1200	30	0.05		
Air layer	0.3	1000	1000	0.025		
Façade stone (travertine)	1.4	950	2000	0.02		
Gypsum-soil and gypsum mortar	0.4	1000	1000	0.03	Dry execution of ACC block 20 cm	
ACC block	0.17	700	1000	0.20		
polystyrene insulation	0.033	1200	30	0.05		
Air layer	0.3	1000	1000	0.025		
Façade stone (travertine)	1.4	950	2000	0.02		

Table 5. Thermodynamic Properties of Introduced Walls

Sample	u-value w/m²k	Admittance w/m²k	Thickness (m)
HCB1	1.30	3.52	0.21
HCB2	1.08	3.63	0.21
L1	1.34	3.57	0.28
L2	0.41	4.01	0.33
A1	0.71	3.77	0.28
A2	0.37	3.85	0.33
15 cm clay with dry facade	0.51	3.82	0.27
20 cm Leca block with dry facade	0.39	4.05	0.32
20cm ACC block with dry facade	0.35	3.98	0.32

8. RESULTS AND ANALYSIS OF THE EFFECT OF TYPE AND THICKNESS OF MATERIALS ON THE THERMAL PERFORMANCE OF EXTERNAL WALLS

The first state: Thermal performance of sample walls regardless of the function of the heating and cooling systems: the dynamical simulation results show that the proposed types of walls behave differently than expected based on their thermal conductivity. Considering the lowest reducing agent and the highest latency, it is anticipated that with the same geometry and structure, among the abovementioned materials, Leca and ACC show better thermal behavior than the clay block. According to the steady-state calculations, the A2 wall with the lowest thermal conductivity coefficient has the best thermal behavior and due to the low reduction coefficient, it has the highest capability in modulating the internal temperature fluctuations relative to the outside fluctuations. In the winter months, compared to summer, the walls behave more as expected than their thermal capacity. This is because the thermal capacity is more useful when the thermal conditions of the environment are changing (unstable conditions). In other words, in winter, the indoor temperature is always higher than the outside temperature. Heat flows are always in one direction (from the inside out), while in the summer months, the building shell is exposed to heat flows in both directions, from the inside out and vice versa, and this is a phenomenon that challenges the early forecasts of the studies performed under steady-state conditions. For this purpose, according to climatic data, from 13 January to 19 January and from 20 July to 26 July were chosen as the coldest and the hottest weeks, respectively and the walls were also examined during these periods.

Table 6. Comparison of the Annual Indoor Temperature with the Outdoor Temperature in Sample Walls without Cooling and Heating Systems (Builder Design Software Output)

Date/Time	A1	A2	HCB1	HCB2	L1	L2	15 cm Clay with the Dry Facade	20cm ACC Block with the Dry Facade	20 cm Leca Block with the Dry Facade	Outside Dry- Bulb Temperature
	(°C)	(°C)	(°C)	(°C)	(°C)	(°C)	(°C)	(°C)	(°C)	(°C)
January	10.25	10.86	7.92	9.57	9.74	11.92	11.38	12.15	12.37	1.56
February	12.87	13.22	11.10	12.42	12.50	14.14	13.59	14.09	14.40	5.15
March	18.18	18.37	16.56	17.77	17.85	19.30	18.85	19.26	19.54	10.64
April	22.58	22.34	21.45	22.31	22.38	23.40	22.10	23.41	23.57	15.76
May	25.81	25.08	25.29	25.70	25.67	26.19	25.94	25.05	26.22	21.43
June	31.00	30.36	30.48	30.78	30.81	31.44	31.22	29.98	31.50	25.62
July	32.70	32.00	32.04	32.48	32.49	33.10	32.89	31.92	33.17	27.94
August	31.91	31.35	31.44	31.63	31.67	32.44	32.23	31.10	32.56	26.75
September	28.01	27.75	26.77	27.68	27.77	28.83	28.58	26.93	29.03	21.55
October	24.84	25.17	22.77	24.28	24.42	26.13	25.64	26.21	26.41	16.05
November	17.97	18.58	15.74	17.35	17.51	19.50	18.97	19.46	19.87	9.00
December	12.51	13.15	10.30	11.90	12.04	14.06	13.52	14.20	14.44	4.03

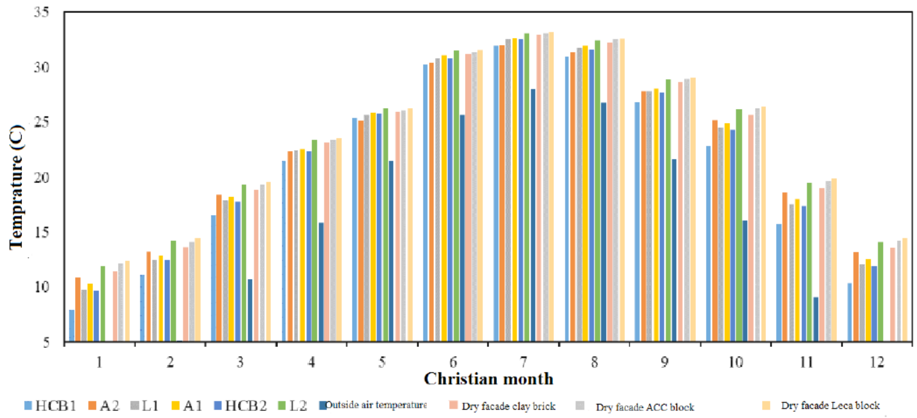


Fig. 2. Comparison of the Annual Indoor Temperature with the Outdoor Temperature in Sample Walls without Cooling and Heating Systems (Builder Design Software Output)

As can be seen in Figure 2 and Table 6, when the cooling and heating systems are not active, the performance of the walls themselves is as follows: in cold months, when the temperature is at its lowest level, among the walls common in Mashhad city, the L2 wall keeps the indoor temperature higher, followed by A2 wall and thus, they outperform than other walls. But in warm months, L2 has poor performance, and A2 and HCB1 keep the indoor temperature lower. Moreover, about dry façade execution, it can be observed that in all seasons, all types of walls perform better than conventional method in Mashhad.

Table 7. Comparison of the Annual Indoor Temperature with the Outdoor Temperature in the Six Sample Walls without Cooling and Heating Systems in the Period From July 20 To July 26 (Design Builder Software Output)

Date/Time	A1	A2	HCB1	HCB2	L1	L2	15 cm Clay with the Dry Facade	20cm ACC Block with the Dry Facade	20 cm Leca Block with the Dry Facade	Outside Dry- Bulb Temperature
	(°C)	(°C)	(°C)	(°C)	(°C)	(°C)	(°C)	(°C)	(°C)	(°C)
2015-07-20	34.02	32.38	33.23	33.80	33.80	34.34	33.13	32.08	33.23	28.34
2015-07-21	34.41	32.74	33.81	34.24	34.20	34.69	33.50	32.49	33.60	30.87
2015-07-22	34.49	33.08	33.97	34.34	34.29	34.72	33.82	32.83	33.92	30.29
2015-07-23	34.56	33.37	33.94	34.38	34.38	34.81	33.42	33.13	33.62	29.83
2015-07-24	34.49	33.49	33.82	34.30	34.30	34.79	33.56	33.26	33.76	29.43
2015-07-25	34.11	33.32	33.37	33.85	33.91	34.50	33.44	33.09	33.53	28.60
2015-07-26	33.92	33.24	33.34	33.68	33.71	34.33	33.28	33.01	33.46	28.17

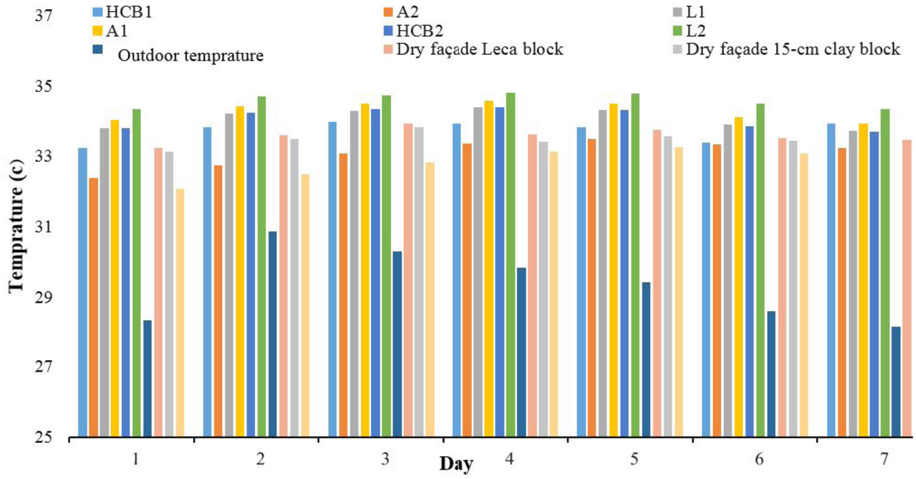


Fig. 3. Comparison of Annual Inside Temperature with the Outside Temperature in Six Sample Walls Without Cooling and Heating Systems in the Period from July 20 To July 26 (Design Builder Output)

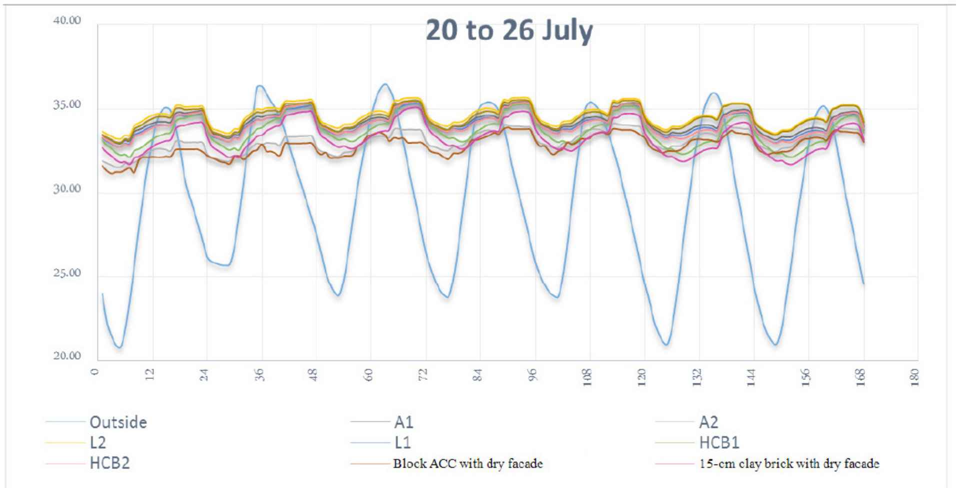


Fig. 4. Thermal Behavior of the Six Sample Walls Common in Mashhad without Cooling and Heating Systems in the Period from July 20 to July 26 (Design Builder Software Output)

As can be seen in Table 7 and Figures 3 and 4, when the cooling and heating systems are not switched on, in the hottest week of the year, the walls A2 and HCB1 keep the indoor temperature at a lower level and perform best, and the wall L2 exhibits the weakest performance, and in the case of a dry façade of any wall, it is observed that this type of facade significantly reduces the indoor temperature in the warmest week.

Table 8. Comparison of the Annual Indoor Temperature with the Outdoor Temperature in the Six Sample Walls without Cooling and Heating Systems in the Period from 13 January to 19 January (Design Builder Software Output)

Date/Time	A1	A2	HCB1	HCB2	L1	L2	15 cm Clay with the Dry Facade	20cm ACC Block with the Dry Facade	20 cm Leca Block with the Dry Facade	Outside Dry- Bulb Temperature
	(°C)	(°C)	(°C)	(°C)	(°C)	(°C)	(°C)	(°C)	(°C)	(°C)
2016-01-13	7.11	7.62	4.23	6.31	6.51	9.25	8.64	9.86	9.56	-4.15
2016-01-14	6.78	7.20	4.00	6.00	6.18	8.87	8.27	9.46	9.17	-2.99
2016-01-15	5.02	5.76	1.78	4.10	4.40	7.16	6.55	7.74	7.49	-9.36
2016-01-16	3.21	4.37	0.46	2.13	2.51	5.60	5.05	6.30	6.10	-5.38
2016-01-17	3.05	4.14	0.11	2.15	2.37	5.24	4.80	5.97	5.77	-2.74
2016-01-18	3.72	4.64	1.46	2.99	3.09	5.60	5.19	6.25	6.04	3.85
2016-01-19	4.94	5.61	3.39	4.40	4.41	6.49	6.09	7.04	6.79	2.62

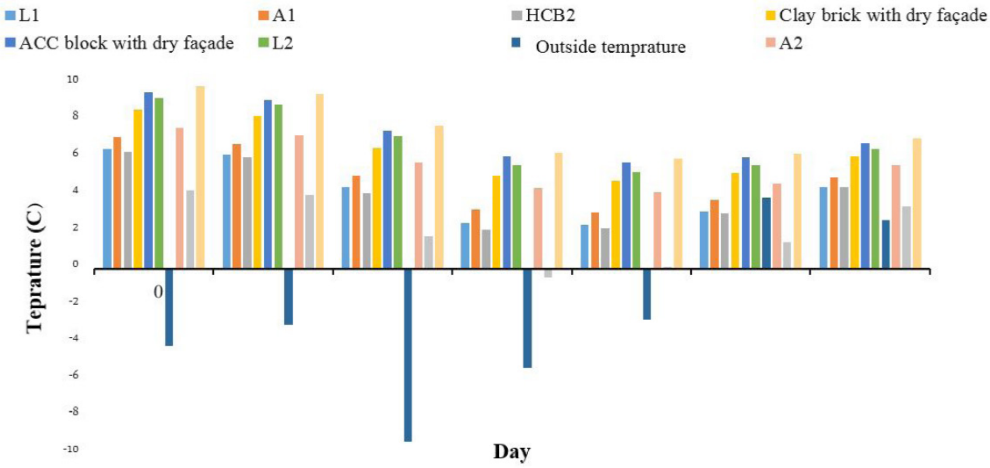


Fig. 5. Comparison of Annual inside Temperature with the Outside Temperature in Six Sample Walls without Cooling and Heating Systems in the Period from 13 January to 19 January

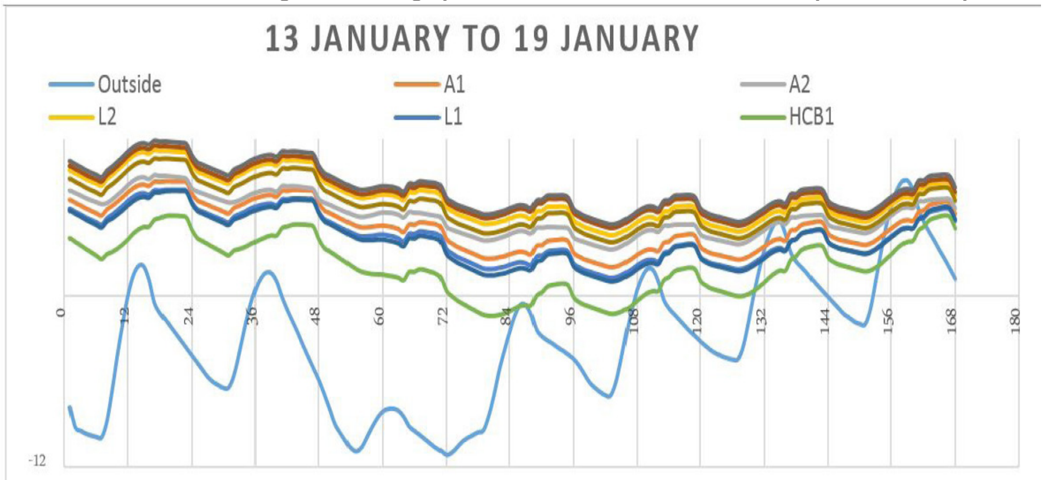


Fig. 6. Thermal Behavior of the Six Sample Walls Common in Mashhad without Cooling and Heating Systems in the Period from 13 January to 19 January

As can be seen in Table 8 and Figures 5 and 6, when the cooling and heating system is not active, in the coldest week of the year, the L2 wall and then A2 wall in terms of maintaining the highest temperature and perform best and the HCB1 wall performs poorly. It shows that in the dry week of the year, this type of application has significantly increased the indoor temperature. For better comparison, the A2 and L2 walls have been further investigated. L2 and A2 behave similarly in winter with thermal coefficients and perform better in indoor air conditioning than in winter, whereas they behave quite differently in summer due to the thermal mass of the materials involved. The crust of the building is surrounded by the environment, especially in hot months and changing weather conditions.

The second state: thermal performance of walls considering cooling and heating system performance: According to climatic data, cooling system was defined for June, July, August and September, and heating system for April, November, December, January, February, and March and the months of October and May have almost thermal comfort and for these two months, the heating and cooling systems were not defined. Considering the weather data and the choice of default residential use, software considers and calculates every hour when there is no thermal comfort and there is a need to use a residential heating and cooling system. Depicting the sum of the cooling and heating loads for each wall indicates the capacity of each structure to consume energy. As can be seen in the diagram, among the common materials in Mashhad, the A2 and L2 structures (as expected from their thermal conductivity) are more effective in reducing energy consumption. In the case of A1 structure, with lower thermal conductivity, it has higher energy consumption than L2 and A2 structures, and its inability to reduce energy consumption is due to its lower latency. This structure releases energy stored in its thermal mass faster than the defined appropriate duration, causing winter cold and summer heat to penetrate the building and thereby increasing energy consumption. Despite their poor thermal behavior in winter, three types of walls, namely L1, HCB1 and HCB2, exhibit overall better summer performance due to their better ability to pass heat and faster release of heat accumulated in the indoor. However, it should be noted that these three structures cause more fluctuations in the indoor temperature due to their lower thermal capacity and, as a result, their higher reduction coefficient and this is undesirable performance. Also, the new dry facade system can be seen to have a significant effect on the energy saving of each wall.

Table 9. Annual Cooling Load Consumption in the Studied External Wall (Total Cooling)

Date/Time	A1	A2	HCB1	HCB2	L1	L2	15cm Ceramics with dry Stone	20 cm Acc Block with the Dry Stone Run	20 cm Leca Block with Dry Stone
	KW/h	KW/h	KW/h	KW/h	KW/h	KW/h	KW/h	KW/h	KW/h
January	0	0	0	0	0	0	0	0	0
February	0	0	0	0	0	0	0	0	0
March	0	0	0	0	0	0	0	0	0
April	0	0	0	0	0	0	0	0	0
May	0	0	0	0	0	0	0	0	0
June	3135.39	2819.69	4023.27	3409.33	3299.01	2984.23	2968.55	2695.71	2839.63
July	4271.19	3661.84	5903.92	4763.35	4571.17	3889.68	3935.79	3538.99	3708.37
August	3456.02	3029.51	4649.83	3817.89	3681.76	3200.25	3207.36	2875.43	3046.42
September	908.151	913.425	1028.98	934.21	917.05	921.53	915.68	913.133	918.78
October	0	0	0	0	0	0	0	0	0
November	0	0	0	0	0	0	0	0	0
December	0	0	0	0	0	0	0	0	0
Total Cooling Load	11771	10425	15606	12925	12469	10995	11027	10023	10513

Table 10. Annual Heating Load Consumption in the Studied External Wall (Zone Heating)

Date/Time	A1	A2	HCB1	HCB2	L1	L2	15cm Ceramics with Dry Stone	20 cm Acc Block with the Dry Stone Run	20 cm Leca Block with Dry Stone
	KW/h	KW/h	KW/h	KW/h	KW/h	KW/h	KW/h	KW/h	KW/h
January	8314.04	6580.1	13534.2	9813.91	9312.62	6383.07	7291.77	6423.63	6326.25
February	5253.1	4108.11	8852.55	9272.96	5944.79	4101.2	4581.29	3965.60	3922.33
March	2231.23	1664.44	4022.26	2740.09	2572.57	1700.24	1889.34	1606.38	1576.63
April	477.92	255.72	1086.26	658.56	577.68	297.48	344.347	263.80	242.606
May	0	0	0	0	0	0	0	0	0
June	0	0	0	0	0	0	0	0	0
July	0	0	0	0	0	0	0	0	0
August	0	0	0	0	0	0	0	0	0
September	0	0	0	0	0	0	0	0	0
October	0	0	0	0	0	0	0	0	0
November	2685.73	1906.03	4890.37	3331.64	3115.07	1791.74	2236.35	1846.66	1804.71
December	6040.01	4744.35	9703.6	7106.34	6770.1	4598.57	5301.63	4643.01	4580.86
Total Heating Load	25002	19259	42089	29923	28293	18872	21645	18749	18453

Table 11. Total Annual Load Consumption of the six External Walls Examined (Total Heating and Cooling Load)

Date/Time	A1	A2	HCB1	HCB2	L1	L2	15cm Clay Block with Dry Stone	20 cm Leca Block with Dry Stone	20 cm ACC Block with the Dry Stone Run
	KW/h	KW/h	KW/h	KW/h	KW/h	KW/h	KW/h	KW/h	KW/h
Total Load	36772	29648	57695	42848	40762	29867	32672	28966	28772

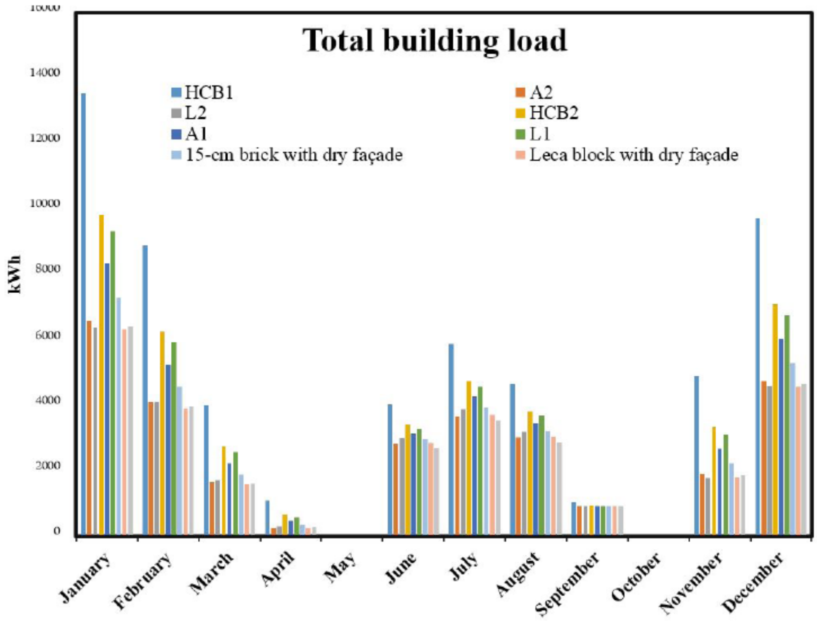


Fig. 7. Total Annual Load Consumption of the Six Common Walls in Mashhad (Sum of Heating and Cooling Load)

According to Figure 7 and Tables 9, 10 and 11, when the cooling and heating systems are active, the sum of the total cooling and heating loads, defined as total load, has its lowest value in the walls A2, followed by L2. So, there is less energy dissipation through these two walls, and the HCB1 wall reveals the weakest performance. Moreover, about the dry façade of each wall, this type has significantly reduced the total load.

9. CONCLUSION

Building shell, as a major intermediary between indoor and outdoor space, plays a significant role in modifying climates and providing comfort to residents, thereby reducing cooling and heating loads. Designing and executing building shells with the ability to provide the highest thermal comfort in the outside with appropriate thermal behavior, and without the help of mechanical equipment, can greatly save energy. The results of dynamical simulation show that the presented types of walls behave differently than expected based on their thermal conductivity. This is due to the periodic response of the building shell to climatic conditions (intermittent behavior of the building shell against changing climatic conditions), which can be interpreted using the thermodynamic characteristics and thermal mass in the building structure. Thermal mass, the most important factor in thermal behavior under unstable conditions, depends on three basic properties of the materials: density, thermal capacity, and thermal conductivity, so that (1) higher thermal capacity increase the amount of heat absorbed per kg of material. (2) Materials with higher density absorb more heat. (3) Moderate thermal conductivity helps to improve the thermal capacity of the material. Steady-state calculations, which lead to the thermal conductivity calculation and are performed under constant laboratory conditions are not a comprehensive method for evaluating the thermal behavior of a building shell. Thermal insulation and thermal mass play different roles in the thermal behavior of the entire building shell, and it is desirable to separately investigate the role of both of them. In the winter, given the relatively stable conditions, materials act based on their thermal conductivity. It is observed that the L2 and A2 walls show better thermal behavior than other wall types. Although these two walls have conductivity coefficients close to each other, in the summer, they behave differently because the materials act differently under unstable and steady state conditions and thermal mass is an important factor in the conclusions. The following tables show the percentages of load reduction and energy dissipation through walls for the six common sample wall in Mashhad and the dry façade execution of three sample walls was investigated. The results were analyzed based on the weakest wall in terms of thermal performance, i.e. HCB1 and the percentages were expressed based on reduction relative to HCB1. The table results are based on the assumption that cooling and heating systems are switched on.

Table 12. Comparison of Annual Indoor Temperature with the Outdoor Temperature in the Sample Walls, Regardless of Cooling and Heating Systems (Design Builder Software Output)

State	Total Load	Heat Transfer through Walls	Percentage of Total Load Reduction	Percentage of Energy Dissipation through Walls
HCB1	57695	43852	-	-
A1	36773	20741	36%	53%
A2	29684	12999	49%	%70
L2	29867	13399	48%	%69
L1	40762	25262	29%	42%
HCB2	42848	27555	26%	37%
Execution of Dry Facade (Clay)	32672	15271	43%	65%
Execution of Dry Facade (Leca)	28966	12894	50%	71%
Execution of Dry Facade (ACC)	28772	11656	51%	73%

As can be seen in Table 12, assuming that the heating and cooling systems are switched on, the weakest wall in terms of thermal responsiveness among the external walls in Mashhad, is 15cm clay (HCB1) and the most efficient wall in terms of energy efficiency and thermal responsiveness is A2. If the A2 wall is used in Mashhad, 49% of the total load and 70% of the wall losses will be saved. Assuming that the cooling system is switched off, the wall A2 has the best performance at the lowest internal temperature in summer, and in winter the wall L2 and afterward A2 have the best thermal performance in the maximum internal temperature compared to outside temperatures. Also, in line with the execution of the dry façade, it is observed that the total load and thermal loss of the wall are reduced. As shown in the table, the dry execution of the wall system greatly helps save energy. This is because there is a gap between the facade and the building, which is filled with air, and in addition to acting as an insulator, air prevents heat exchange between the exterior and the interior of the building and provides the use of thermal insulation behind the façade, it also makes it possible to reduce the possibility of moisture penetration through the facade materials to the walls of the building. Other benefits of these systems include its quick implementation, reduced weight of the building, recyclability of materials and more. By scrutinizing all these advantages, it is concluded that it is better to use a dry facade system instead of the common walls in Mashhad to help save energy and materials.

According to the findings of this study, in the design process, it is suggested that designers of new systems and new execution systems and up to date details in advanced countries design and evaluate them in Design Builder in terms of thermal conditions to taking a small step towards saving fuel and energy by exploring new and different details and considering each space's usage. It is also recommended that designers of other parts of the building that are affected by energy waste, including roof, openings dimensions, etc., evaluate the city and site using climate software such as Building Design software and using these selective results have correct decisions and minimize the amount of energy wasted in the space.

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