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A Study on Application of Modern Construction Materials and Comfort Properties of Buildings, Influence of Temperate and Humidity

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Abstract

This study compares the results of applying modern wall construction materials for the climatic condition of Southern Caspian regions in the north of Iran. The objective is to search for energy-efficient construction techniques suitable for this temperate and humid climate. This was pursued by analysing thermal comfort within building constructed from variety of modern materials. The wall constructions currently applied are introduced along with their dynamic and thermal properties. To analyse and compare the thermal behaviour and appropriateness of different building materials, a computer simulation is performed. The results from simulation analysis highlighted the important effects of thermal admittance and thermal mass along with u-value on thermal performance of the materials. They show that building with hollow clay tiles and lightweight concrete blocks with insulation had a better performance in achieving the preferred thermal comfort, while decreasing energy cost. This research contributes to the promotion of passive and low energy design towards a sustainable future.

Keywords: Thermal comfort, Building materials, Energy efficiency, Temperate and humid climate

1. Introduction

The future of energy production and distribution is worrying due to the increasing consumption and reduction of recoverable resources. In Iran, building sector allocate 40 percent of the country's energy usage while heating and cooling have the highest share [1]. The index of energy usage in the building sector is very high, and the household sector's average fuel consumption in Iran is 6.2 times higher than the European countries [2].

In 2011, 41% of the total population in Iran were aged between 15-34 years [3]. Besides, the increasing migration of the population to the cities has caused a serious demand for more dwellings and faster construction. According to the Building and Housing Research Center, the construction of residential buildings had an 18% increase between March and October 2011 [4]. This high rate of energy consumption highlighted the necessity of applying energy saving and efficiency boosting strategies.

In the interest of sustainable development and minimizing energy consumption regulations for evaluating building performance are developed [5-9]. The Code 19 has been introduced by the Iranian Ministry of Housing and Urbanism [10]. According to this guideline the whole building heat loss should be less than the equivalent building constructed with U-values compliant with the code. These codes and standards usually consider using less energy to design energy efficient buildings [11]. However, low energy usage does not necessarily correspond to a higher energy efficiency [12, 13]. The knowledge about the climate and passive strategies are required to control and provide the right design approaches for energy minimization. To maintain the energy efficiency in the building sector, four main principles should be considered as [14] :

− Improving the building envelope (as shade, windows, materials, etc.)
− Changing the occupants' behaviour
− Applying energy efficient systems

− More renewable energy usage.

The building envelope is the major interface between indoors and outdoors, and affects the comfort sense for occupants and heating/cooling loads of the building. The effects of materials on the thermal performance of the building are considerable. It is the thermophysical properties of the construction materials, which determines the rate of heat exchange, and provides one of the aspects of thermal comfort within any building. Due to their inherent properties, different building materials respond differently to the climatic conditions. The general criteria to be followed in the specification and construction of external building materials are [15]: the thermal insulation level, environmental impacts, conductivity and heat storage capacity. The national building guidelines normally concentrate on steady-state performance and utilization of insulation in wall construction [16]. In steady-state evaluations, the thermal conductivity of materials are considered, while the influence of heat capacity is ignored [17]. However, the cyclic behaviour of materials and effects of thermal mass have great influence on ameliorating building thermal performance.

Thermal mass relates to the heat capacity of materials that cause heat absorption, store and release [18]. The building component such as walls, partitions, ceilings, floors, and furniture have the capacity for storing thermal energy. This characteristic helps to control the indoor temperature by absorbing and gradually dissipating heat, while reducing mean radiant temperature [19]. However, it is more efficient for buildings with part-time usage such as offices that are unoccupied during nights, and the absorbed heat can be cooled down with night time ventilation. Moreover, the results from the computational comparison of six different envelope configurations showed that the position of the thermal mass in the building envelope has no effect on energy efficiency of high rise buildings in cold climates [20]. In fact, to optimize the thermal mass, building orientation, ventilation, thermal insulation, applied cooling system, and occupancy pattern should be considered.

In modern methods of construction, un-fired clay and brick are replaced by lightweight and recyclable materials [21, 22]. Application of these materials provide better solutions for reducing the usage of natural resources, but controlling the environmental impacts of the building construction is still debatable. The vernacular architecture of the regions in moderate and humid climate of Iran, use lightweight wooden walls with low thermal mass in order to adjust the thermal conditions. However, nowadays modern construction materials such as hollow clay blocks, autoclaved aerated concrete blocks, light expanded clay aggregate blocks and concrete panels are applied in replacement. Some of these materials are combined with insulation layers for improving the thermal performance of the constructed walls. The main objective of the current research is to investigate the effects of applying modern materials on indoor thermal conditions. Although there are several studies on evaluating building thermal performance and influence of materials on improving energy efficiency such as references [16, 22-24], the considered climatic conditions and types of selected materials reported in this paper are distinctive consideration to improve energy efficiency in buildings design. To this end, the computer modelling software, Ecotect, was used to simulate the thermal performance in a case study building.

2. Envelop properties

This study mainly focuses on thermal performance of a range of modern wall constructions used in Iran. Based on interviews with people involved in the construction industry and field observations of the authors, following results have been obtained. Conventional wall constructions that are applied in buildings of the cities in north of Iran have been specified as: Hollow Clay Blocks (HCB), Autoclaved Aerated Concrete blocks (AAC), LECA blocks, 3D panel, and Insulating Concrete Forms (ICF).

Most of the responded experts appeared to have experience in more than one material. On average the HCB was the most common material used in their projects. HCB are burned-clay building materials, which are lighter than cement blocks of the same size. This material is gaining more popularity because it is readily available, easy to build with, and easy to maintain. Moreover, decreasing the dead load of a building and faster construction can reduce the construction costs in this system. However, difficulties in applying changes in the middle of the site work are one of the issues with this system.

LECA Blocks are made by mixing Leca aggregates with cement and water, while adding sand will increase the concrete strength, and makes the surface of the block smoother. It has also lower weight and thermal conductivity compare with normal concrete blocks. The evaluations identified that Leca blocks are readily available in construction market, and easy to assemble and to work with. Nonetheless, obstacles of water and electricity plumbing according to the stiffness of the material are a challenging issue. Some constructors prefer

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the use of LECA over clay blocks to achieve a better performance in damp controlling. However, it is not accepted by all practitioners, and better performance of the material is perceivable when the insulation is added.
AAC, is made of fine aggregates, cement, and an expansion agent that causes the mixture to be aerated. According to the porosity of the material it offers good sound and thermal insulation properties. However, greater initial cost than other materials such as HCB and difficulties during the construction period (detachment between AAC blocks and interior plaster) have reduced the application of the material.
3D concrete panels consist of welded wire space frame integrated polystyrene insulation core and layers of concrete applied to the both sides. This combination creates a truss behaviour that presents rigidity for full composition behaviour [25]. It is considered as an economical and cost effective technique, which reduces the buildings' dead load noticeably. The constructed walls are also well insulated, and it is easy to place the water and electrical plumbing inside the walls during the construction. However, sequential assembly makes the required changes difficult during or after the construction.
ICF is a system of formwork for concrete. The forms are interlocking modular units that are dry-stacked (without mortar) and filled with concrete. The units lock together somewhat similar to Lego bricks and create a form for the structural walls or floors of a building. This construction system has become popular for both low rise commercial and high performance residential buildings as provides high level of energy efficiency and natural disaster resistant [26, 27]. However, according to the modernity of the system it is difficult to find expert workers to erect the buildings.

3. Ambient conditions

The study area is located in Babolsar, Iran, which is situated at latitude **36 °25′** to **36 °40′** in north and longitude **52 ° 29′**to **52 ° 39′** in west. The height of the city from the sea level is -21 meters [28]. Being close to the Caspian Sea, the humid and moderate conditions are emphasized with heavy rainfall in autumn and winter. The air temperature in summer is ranged between 25°C-30°C during the day, and 20°C-23°C during the night, and it is usually above 0°C in winter.

4. Simulation

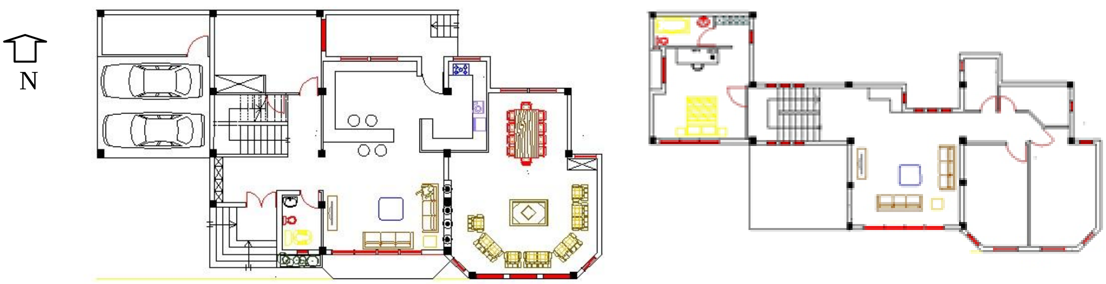
Efficient assessment of buildings thermal performance has an important effect on the reduction of energy consumption for heating and cooling. Computer simulations are applied to examine the conditions that are not tested in reality yet, or to analyze and compare different building systems before construction. A test unit was modeled in Ecotect5.0 software and variant materials were nominated in order to measure the thermal condition of the unit. Ecotect 5.0, is a conceptual design analysis tool designed by Dr. Andrew Marsh of Square One research, that features shading design, lighting, acoustic and thermal analysis functions as well as wind flow[29]. This software is capable to simulate the performance of a building under unsteady-state conditions using real climate data (here Babolsar city). To analyze the output, Ecotect uses a wide range of informative graphs, which can be saved as Metafiles, Bitmaps, or animations. Many researchers have also used this tool to investigate the required design configurations in their studies [30-33].
By applying this software, the alternative graphs of hourly temperatures, discomfort period and monthly heating and cooling loads of the house in respect to thermal neutrality comfort band were obtained and the effects of different materials on thermal comfort in the same house were observed. A two-story villa house was used as a case study for the analysis and generation of a 3D model. This type is the ubiquitous form of housing in this region in single or double stories. The planning of the houses is usually consists of living spaces, kitchen, and bedrooms with toilets. The master bedroom, bedrooms, and toilets are in the second floor. The big windows on the main facades (usually north and south) provide cross ventilation that is effective for the humid climate. The plans and 3D model of the unit are shown in Figures1 and 2. The building materials are either chosen from Ecotect library or created from the user library. The property values for these materials are calculated from Ecotect material property. The material descriptions of the simulated house are shown in tables 1 and 2.
A model in Ecotect is divided into a series of individual spaces known as "zones" for an accurate thermal analysis. In this case study, the model was divided into 18 zones namely: entrance, kitchen, cooking room, guest room, living room, sitting room1, sitting room 2, master bedroom, bedroom1, bedroom2, bath, WC1, WC2, store, deck, stair case and the parking which considered as outside zone. The zone properties have been deliberated according to the literature review and the condition of the house.

Table 1: Wall type material description. (Source: Ecotect calculations)

Wall Material description		U-Value (w/m^2k)	Thickness (cm)	Thermal admittance (w/m^2k)	Thermal decrement (0-1)
AAC1	20mm Marble with 30mm mortar with 200mm Aerated Block with 30mm plaster	0.71	28	3.57	0.38
AAC2	20mm Marble with 30mm mortar with 100mm Aerated block with 50mm polystyrene with 100mm Aerated block and 30mm plaster.	0.37	33	3.59	0.16
HCB1	20mm Marble with 30mm mortar with 150mm hollow clay tile with 30mm plaster	1.3	23	3.85	0.55
HCB2	20mm Marble with 30mm mortar with 50mm polystyrene with150mm hollow clay tile with 30mm plaster	1.08	23	4.0	0.36
LECA1	20mm Marble with 30mm mortar with 200mm hollow, lightweight concrete block tile with 30mm plaster	1.34	28	3.84	0.59
LECA2	20mm Marble with 30mm mortar with 100mm hollow, lightweight concrete block with 50mm polystyrene with 100mm hollow, lightweight concrete block with 30mm plaster	0.41	33	4.06	0.31
3D panel	30mm plaster with 60mm lightweight concrete with 50mm polystyrene with 60mm lightweight concrete and 30mm plaster	0.14	21	2.93	0.64
ICF	15mm plaster with 50mm polystyrene with 150mm lightweight concrete with 50mm polystyrene and 15mm plaster	0.08	28	1.5	0.04

Table 2 : Material properties for the case study building. (Source: Ecotect calculations)

Material description		U-Value (w/m^2k)	Thermal admittance (w/m^2k)
floor	100mm thick suspended concrete floor plus ceramic tiles and plaster ceiling underneath.	2.9	5.21
ceiling	10mm suspended plaster board ceiling, plus 50mm insulation, with remainder (150mm) joists as air gap	0.5	0.9-210
Roof	50mm thick clay tiles with 75mm air gap and 0.6mm aluminium foil and with 10mm plaster	1.82	2- 132
Door	40mm thick hollow core plywood door	2.98	0.65- 40
Window	Double glazed with aluminium frame (no thermal break), emissivity of 0.10	2.41	2.38-



First floor Second floor

Figure 1: First floor and second floor plan of the case study building

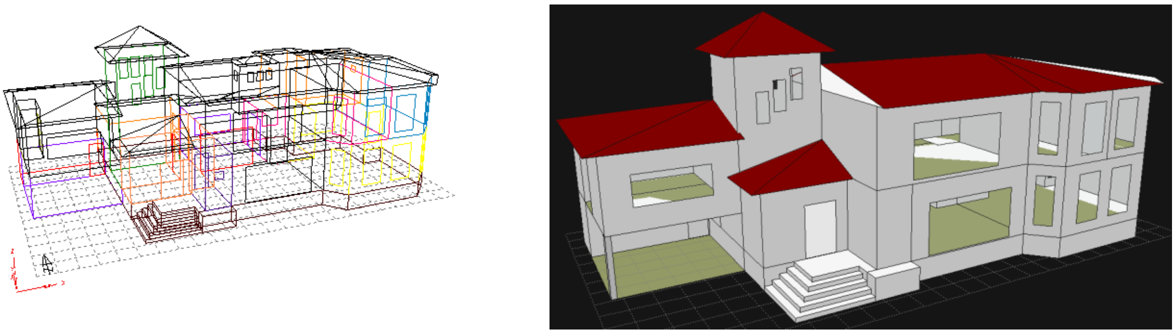


Figure 2: 3D model of the house built in Ecotect software

4.1. Weather data analysis

To analyse the routines in Ecotect the hourly data for weather in a full year is required. According to the variety of formats for electronic weather files, the software includes a weather tool to analyse and convert weather data to a recognisable format for Ecotect. The weather data for this study was obtained from White box Technologies metrological office and was reformatted for thermal analysis [34].

Figure 3 presents a 10-year average (2004-2014) of daily maximum and minimum values of outdoor air temperatures for each month against thermal comfort bands derived from the thermal neutrality temperatures for Babolsar. Based on the adaptive comfort standard [35], the bounds of comfort temperature were calculated using average monthly temperature as followes:

$$T_{(N)} = 0.31T + 17.8$$

where T is the average monthly temperature. As can be seen, higher differences between the temperature and comfort condition is perceivable in December-January in winter and July- August in summer**.** The Ecotect Analyses conducted which will be presented in the following section are as follows: Monthly Discomfort Degree Hours, Temperature Distribution and comfort condition throughout the year.

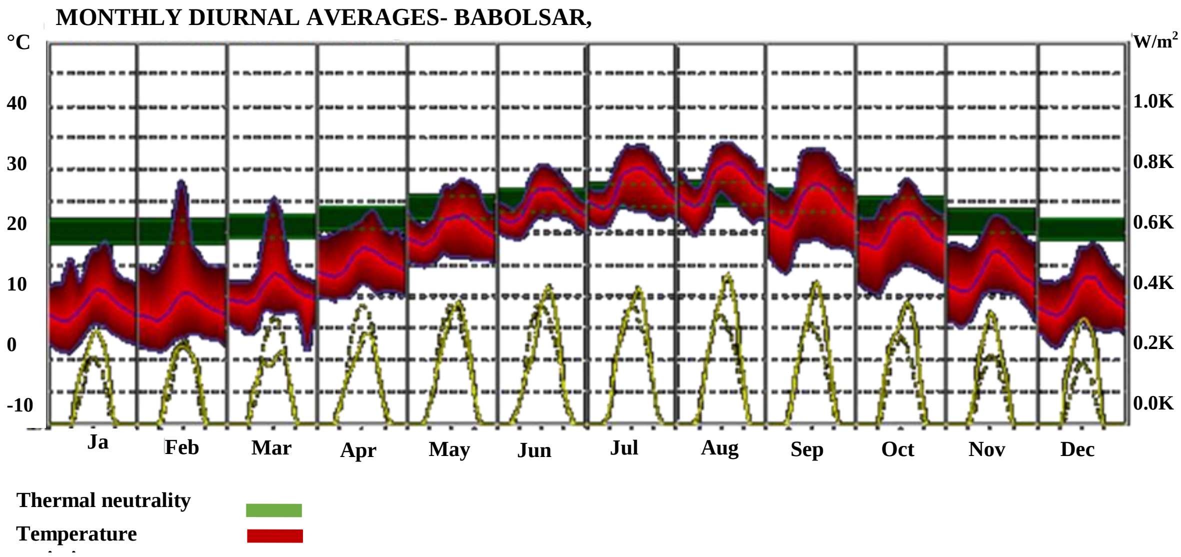


Figure3: Babolsar weather data, (Source: Weather tool 1.1**)**

5. Results and discussion

The results from the Ecotect simulation provide useful information for investigation of wall performance according to the nominated u-value and other thermal properties. The reduction in cyclical temperature on the inside surface compared to the outside surface is known as the decrement[36].Meaning that, a material with a decrement value of 0.04 which experiences a 20 degrees diurnal variation in external surface temperature would experience only 8 degrees variation in internal surface temperature. Based on the properties of the materials wall type ICF, with lowest u-value have the highest capability for depletion of outside temperature swing according to its lowest decrement value. On the other hand, as presented in table 1, LECA2 has the highest thermal admittance which is the material's ability to absorb heat and release it to the environment over time. Meaning that the higher the admittance value shows the higher thermal storage capacity of the material. Accordingly, it is expected that LECA2 dampen the weather conditions.

5.2. Temperature Distribution

Annual internal temperature distribution graph of the case study building shows the number of hours a particular internal temperature is encountered over the entire year, by applying different building materials (Figure 4). The vertical axis shows the hour count while the horizontal axis shows the temperature. The wall types AAC2 and ICF, illustrate variations of higher inside temperatures throughout the year according to the insulation layers which prevent the heat exchange even at summer evening and night hours.

Table 3 shows the percentage of time providing comfort condition according the sensible temperature during the year. As the Ecotect analysis deliberated hollow clay blocks with thermal insulation stay comfortable 33.4% for the longest period. While ICF wall has the shortest period of comfort among the group which is 30.4%. The AAC2, HCB1 and LECA1&2 are in comfort for approximately same percentage as 33.0 %- 33.3%. Besides, the 3D pane and AAC1 also provide similar comfort conditions as 32.3% and 32.4% according to the effects of thermal mass and lower conductivity which reduce the required thermal exchanges in warm seasons and cause discomfort.

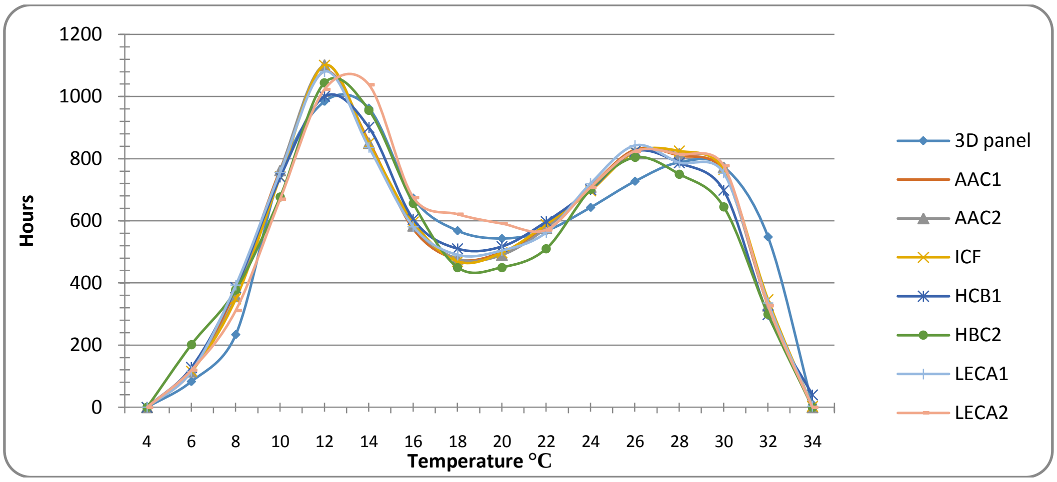


Figure 4: Annual temperature distribution of the case study building by application of different wall materials. (Source: Values from Ecotect, graph from M.S. Excel)

5.2. Monthly Discomfort Degree Hours

Based on adaptive and static comfort theory, the case study building has shown different discomfort levels according to different building materials in natural ventilation conditions. Monthly discomfort graphs of the house were imported to a spread sheet to show the effects of different building materials month by month according to adaptive (free run) comfort model (Figure 5). Discomfort conditions represent the times when the inner temperature is falls outside comfort boundaries and according to the graph the shortest bars represent the most comfortable situation amongst the group. It could be perceived from the figure that hollow clay blocks with thermal insulation has shown better comfort conditions in warm season (July and August), but worse comfort condition in cold months of the year (December and April).

The autoclaved aerated concrete and hollow concrete blocks without insulation layer were acting similarly throughout the year, whereas 3D panel showed similar properties as ICF panel. According to the lower u-values of AAC2, 3D panel and ICF among the other materials, less variations of inside temperature are perceivable. Comparing the thermal performance of the materials with similar u-values (ICF panel & 3D panel) or (AAC2& LECA2) has shown that these materials provide similar thermal condition in winter. While, in summer materials with different thermal properties (3D panel & HCBC2) have similar thermal performances. One of the reasons could be the effects of thermal mass on thermal conductivity of the materials especially in warm season.

Table 3: Annual percentage of comfort condition for different wall materials (Source: Values from Ecotect, table from M.S. Word)

	3D panel		AAC1		AAC2		HCB1		HCB2		LECA1		LECA2		ICF	
TEM	Hour	Percent%	Hour	Percent%	Hour	Percent%	Hour	Percent%	Hour	Percent%	Hour	Percent%	Hour	Percent%	Hour	Percent%
0°C-2°C	0	0	0	0.0	0	0.0	0	0.0	0	0.0	0	0.0	0	0.0	0	0.0
4°C	83	1.3	115	1.3	115	1.3	128	1.3	202	1.3	116	1.3	120	1.3	116	1.3
6°C	234	3.8	379	4.3	357	4.1	385	4.5	378	4.5	393	4.5	312	4.0	349	4.0
8°C	748	8.7	765	8.7	762	8.7	740	8.7	677	8.8	756	8.6	670	8.8	741	8.5
10°C	984	12.6	1081	12.3	1101	12.6	1000	12.3	1044	12.3	1080	12.3	1023	12.6	1100	12.6
12°C	962	9.7	856	9.8	850	9.5	900	9.6	956	9.7	836	9.50	1038	9.7	849	9.7
14°C	673	6.8	574	6.6	584	6.7	605	6.6	656	6.4	581	6.60	675	6.6	596	6.8
16°C	568	5.4	476	5.4	478	5.5	510	5.5	450	5.5	490	5.6	621	5.5	469	5.4
18°C	543	5.5	499	5.7	490	5.6	517	5.8	450	5.8	504	5.8	591	5.6	497	5.7
20°C	568	6.6	580	6.6	577	6.4	597	6.4	510	6.5	562	6.40	571	6.5	588	6.7
22°C	643	7.9	710	8.1	709	8.1	700	8.2	701	8.3	720	8.2	708	8.1	696	7.9
24°C	727	9.4	829	9.5	822	9.4	823	9.6	804	9.6	842	9.4	824	9.4	821	9.4
26°C	788	8.4	810	8.20	816	9.3	786	9.0	750	9.1	787	9.0	814	9.3	824	9.4
28°C	774	8.8	759	8.7	772	8.8	698	8.6	645	8.6	754	8.6	777	8.9	765	5.7
30°C	548	4.0	327	3.7	327	3.7	298	3.8	299	3.6	336	3.8	327	3.7	346	3.9
32°C	10	0.0	0	0.0	0	0.0	40	0.0	0	0.0	3	0.0	0	0.0	3	0.0
Comfort	2921	32.30	2929	32.4	2924	33.0	2908	33.2	2928	33.40	2911	33.0	2917	33.30	2929	30.4

As demonstrated by the simulation, in winter months, the u-value has stronger effects on the thermal conductivity of the materials and decrease the discomfort hours in the house. In fact, when the thermal condition of the place has higher fluctuation the influence of the u-value is stronger [37, 38]. This effect is caused because in winter the internal temperature is usually higher than outside cold temperature and the heat flow happens from inside to outside, but, in summer it may happen in both sides.

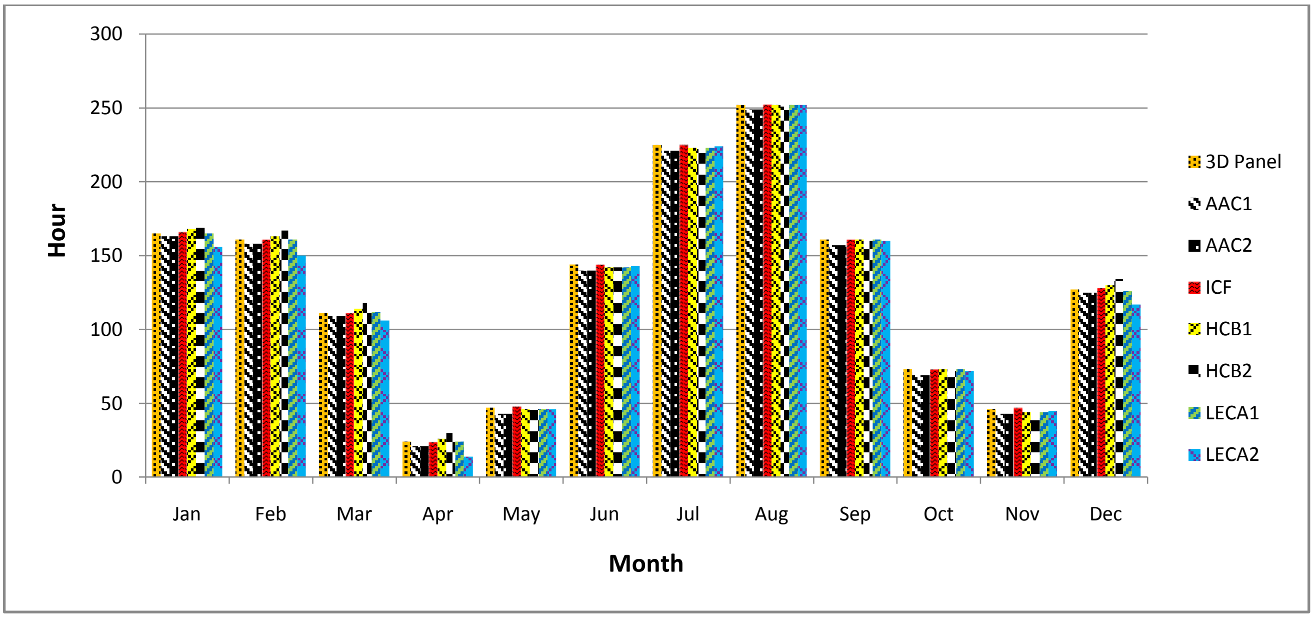


Figure 5: Discomfort degree hours of the case study building according to different building materials. (Source: Values from Ecotect, graph from M.S. Excel)

Conclusions

This study focused on investigating the thermal performance of wall construction materials in residential buildings in north of Iran. It concentrated on modern building materials with respect to increasing the thermal comfort of the occupants while decreasing the heating/cooling loads of the building. The results from the field investigations and interview with the experts have identified that the availability of the materials, cost effectiveness and reduction of the building's dead load are the most important criteria in selection of the materials. Whereas, difficulties in finding expert workers, placing water and electrical plumbing in walls, and applying changes in the middle of the construction were the main hindrances.

Furthermore, a computer model using local weather data was applied to understand the behaviour of the case study building, encompassed different building envelope materials. The results highlighted the effective roles of thermal insulation layers and thermal mass on the thermal performance of the materials. It was shown that while insulating concrete forms and autoclaved aerated concrete with insulation layer have the lower u-values among the introduced wall types, hollow clay blocks and hollow concrete blocks without the insulation layers, have better overall performance in terms of controlling thermal conditions and accommodate comfort for the occupants throughout the year. Thermal insulation is further needed if a relatively lightweight material such as hollow brick will be chosen for the climate of Babolsar. The problem of overheating would easily be overcome by night ventilation to maintain the comfort in summer if insulated hollow brick is preferred to use. Further analysis needs to be done to predict the effects of improving natural ventilation and shading of the walls during hot seasons, on thermal comfort and their means of effectiveness. The completion of this study would assist for suitable material selection and appraise the environmental parameters to measure the difference between conceptual design and the realized ones.

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