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ECONOMIC AND THERMAL PERFORMANCE OF THERMOSTONE IN QATAR

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ABSTRACT

This paper is concerned with the performance characteristics of thermostone as a building material, and their comparison with those of hollow concrete blocks. Carrier Advanced Load Program (E20-II) was used to estimate the annual cooling load of a typical residential Qatari house. A number of combinations of walls and roofs for the house have been used, and the annual electrical energy to air-condition the model house for these combinations are estimated. Comparison of the results revealed that a house whose walls are built from thermostone blocks would consume 25% to 30% less electrical energy than one whose walls are built from hollow concrete blocks. An economic analysis has been performed for these combinations of roofs and walls. The results show that building with thermostone blocks can cut the annual cost of electricity by 28% to 34% as compared to building with hollow concrete blocks.

INTRODUCTION

The weather in Qatar is quite hot and humid during the summer, and mild during the winter; midday temperature in July and August can reach as high as 46 ^{O}C with the humidity exceeding 85 percent. In the winter there is less humidity, and temperatures range between 10 ^{O}C and 20 ^{O}C. Therefore, it is not surprising to know that virtually all buildings in the country require air-conditioning during the summer as nobody could withstand the severity of the weather during almost 8 months of the year.

The electrical energy consumed by air-conditioning equipment, which makes life comfortable for the people during these months, is quite high, and puts a great deal of burden on the state of Qatar in power generation.

Quite often power is shedded during the months of July and August as demand for electricity surpasses the supply capability of the available power generating stations. The increase in demand for electricity during the eight months of severe weather is attributed mostly to the load (cooling load) required for the air-conditioning of residential, commercial, and industrial buildings. This increase is quite significant; in 1993, the ratio of maximum power generated in the summer during peak days to maximum power generated in the winter during minimum days is about 2.75.

In order to minimize the electrical energy consumed by air-conditioning systems, the cooling load required to make a space within a building comfortable must be minimized. Several methods are available for achieving this task. One method is to increase the thickness of the walls and roofs of buildings so as to increase their thermal resistances, which reduces the amount of heat transferred from the uncontrollable environment on the outside to the controlled environment on the inside. Another method is to increase the thermal resistances of walls and roofs by using materials of low thermal conductivity or by adding insulation to both walls and roofs. In Qatar, the most widely used material for building is concrete. Walls are usually constructed from hollow concrete blocks, and roofs are constructed from reinforced concrete and supported by reinforced concrete columns.

Although, the government of Qatar had set a policy on the thermal properties of roofs and walls of governmental buildings, most of the people are still constructing their houses from hollow concrete blocks without insulation. The policy requires that the heat transmittance (U) value for walls must be less than or equal to 0.741 $W/m^2\ ^oC$, and that for roofs must be less than or equal to 0.57 $W/m^2\ ^oC$. These values are quite low and could not be achieved for walls made of hollow concrete blocks of 20 cm thickness in the hot weather of Qatar.

By proper selection of building materials, electrical energy consumed by Air-Conditioning systems can be reduced. Energy conservation in buildings has been the subject of many researchers, and since it is a complex matter, some researchers have concentrated in developing computer programs that facilitates the analysis of energy performance in buildings (1-8). One famous program is the DOE-2.1A developed by the Lawrence Berkeley Laboratory for the United States Department of Energy (5). It is a public domain program and can be used by engineers and architects in designing energy efficient buildings. A similar program, though commercial, is the Carrier E20-II, which can calculate the cooling load of a building and, like the

DOE-2A, has the capability of performing hour-by-hour energy analysis (7). The E20-II program is used in this study because of its availability. Other researchers have concentrated in using such programs to compare the energy performance of available building materials. This study falls into this category, and our objective is to find out whether thermostone blocks are energy efficient and economical in the state of Qatar. Another such study, and related to the Arabian Gulf, was done in Dhahran, Saudi Arabia (9). The study has concentrated in the energy and economic performance of red-clay bricks as compared to sandlime bricks, concrete blocks, and prefabricated concrete walls. The effect of insulation was not considered and only two type of roofs were considered. Other studies have concentrated on experimental data as related to thermal conductivity, porosity, and other relevant properties of building materials (10).

ESTIMATION OF COOLING LOAD

Computer Simulation

The annual cooling energy for a model house built from hollow concrete blocks and that for the same model house built from solid thermostone blocks are simulated using the Carrier Advanced Load Program (E20-II). Details on the E20-II program are found in (7). A schematic of a solid thermostone block and that of a hollow concrete block are shown in figures 1 and 2 respectively. The addition of insulation is also considered for both materials. For insulated walls made of hollow concrete blocks, a 4-cm polystyrene extruded insulation sheet is put between two hollow concrete blocks of the type described in figure 3. Similarly for insulated walls made of solid thermostone blocks, a 4-cm polystyrene extruded insulation sheet is put between two solid thermostone blocks half the size of that described in figure 1.

The program requires the thermal conductivity of the wall and roof materials. The thermal conductivity of a thermostone block and that of a hollow concrete block are 0.383 W/m°C and 1.443 W/m°C respectively (11). They are valid only for the shapes described in figure 1 and figure 2 respectively. The thermal conductivity of the block described in figure 3 equals 0.960 W/m°C (9).

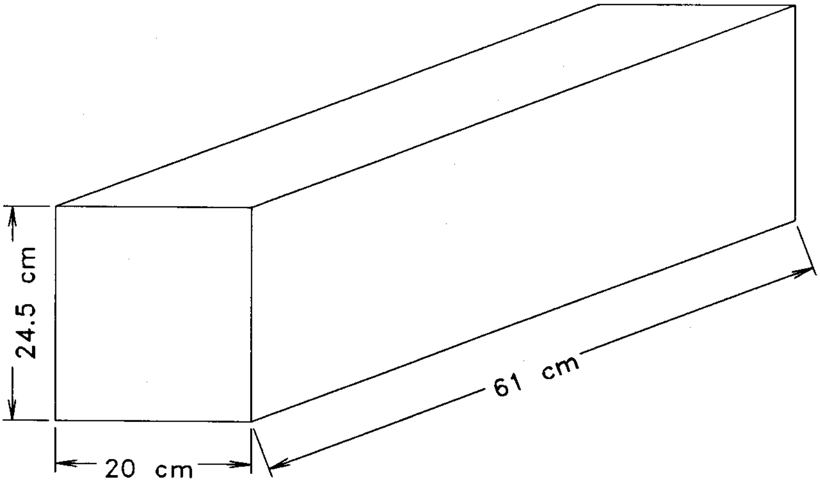

Fig. 1. Detailed description of a thermostone block

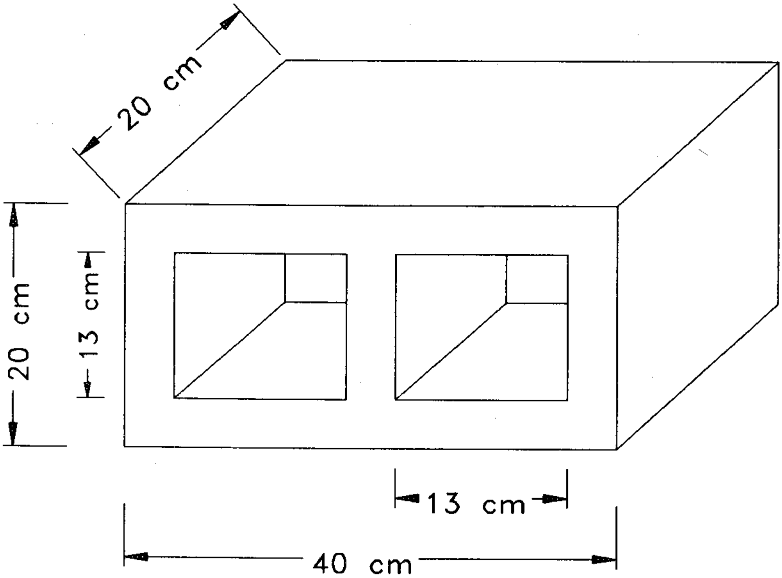

Fig. 2. Detailed description of a hollow concrete block

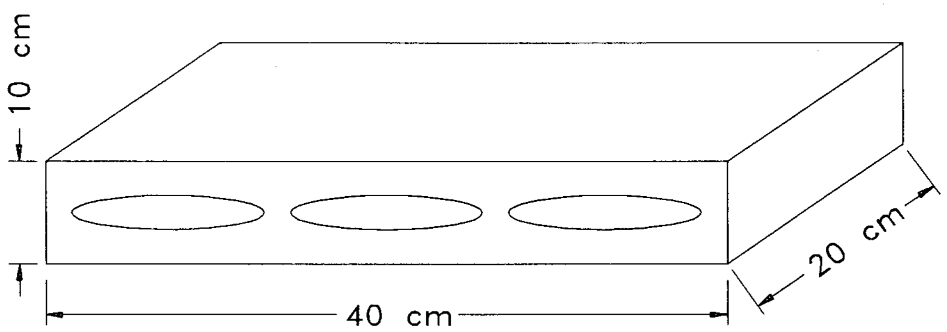

Fig. 3. Detailed description of the hollow concrete block used with 4- cm polystyrene extruded insulation sheet

A schematic of the ground floor plan of the model house is shown in figure 4. It is assumed that six people are living in the house, and that all people are present in the house from 8:00 PM to 7:00 AM and from 2:00 PM to 5:00 PM, fifty percent of them are present from 7:00 AM to 2:00 PM, and eighty percent of the them are present during the rest of the hours of the day. It is also assumed that a temperature of 25 ^{0}C and a relative humidity of 50 % are maintained throughout the year.

The model house has only one floor. Its building-envelope (roof plus outside walls) is made of about 194 m^2 of roof area and about 190 m^2 of outside walls. It also has about 24 m^2 of windows. We had to split the house into simple and complex spaces. A simple space has only two exposures to the outside. While a complex space can have up to eight exposures. For example, the Majlis was entered as a complex space, while the rest of the spaces were entered as simple spaces. Details concerning each space are shown in Table 1.

For this study, we have considered six different type of roofs and four different type of walls, and our objective is to determine which roof-wall combination is the most economical. Roof 1, 2, and 3 are not insulated and they are shown in figure 5. Roof 4, 5, and 6 are insulated and are shown in figure 6. Wall 1 is made of hollow concrete blocks and wall 2 is made of solid thermostone blocks. They are not insulated and are shown in figure 7. Wall 3 and 4 are insulated and are made of hollow concrete blocks and solid thermostone blocks respectively. They are shown in figure 8. All roofs are described in details in Table 2 and all walls are described in details in Table 3.

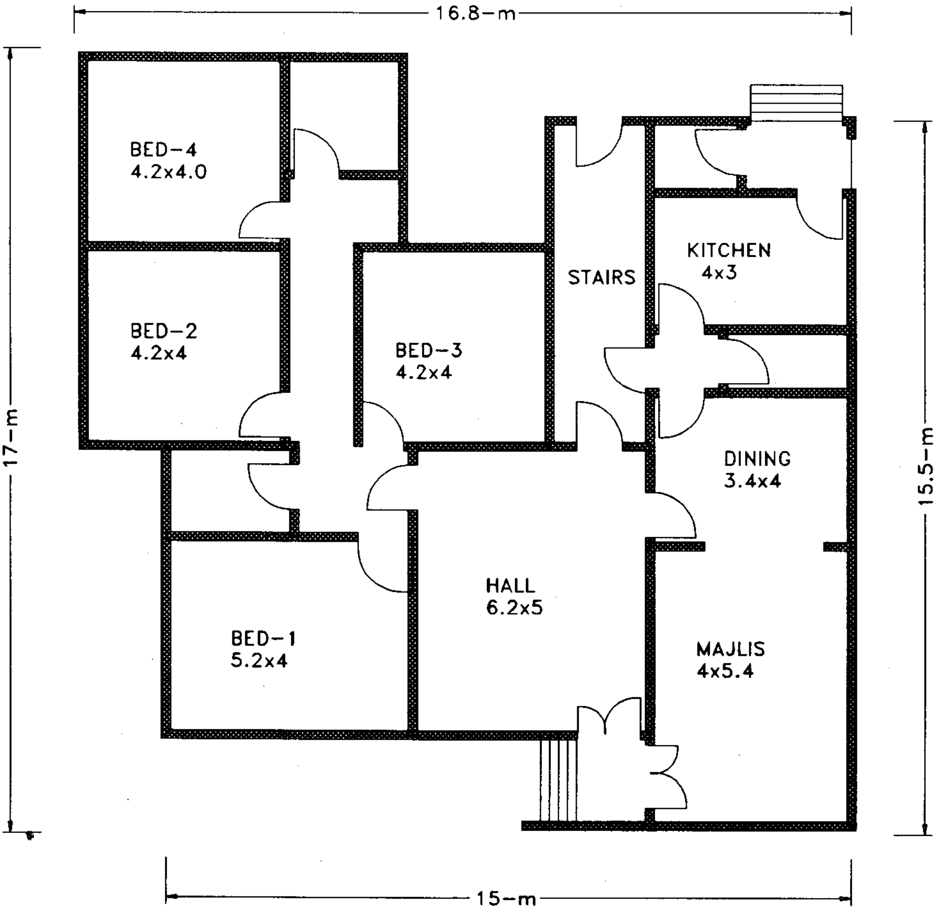

Fig. 4. Ground floor plan of the model house

For roofs, the U-values are found using the following equation:

$$U = \frac{1}{\frac{1}{h_{ri}} + \frac{t_{plaster}}{k_{plaster}} + \frac{t_{c1}}{k_{concrete}} + R_{asphalt} + \frac{t_{insulation}}{k_{insulation}} + \frac{t_{c2}}{k_{concrete}} + \frac{1}{h_{ro}}} \tag{1}$$

and for walls, the U-values are found from the following equation:

$$U = \frac{1}{\frac{1}{h_{wi}} + \frac{t_{plaster}}{k_{plaster}} + \frac{t_{block}}{k_{block}} + \frac{t_{insulation}}{k_{insulation}} + \frac{t_{plaster}}{k_{plaster}} + \frac{1}{h_{wo}}} \quad \textbf{(2)}$$

where

- h_{ri} = 6.13 W/m^2 °C = the roof inside heat transfer coefficient,
- $t_{plaster}$= 13 mm = the thickness of plaster,
- $k_{plaster}$ = 0.797 W/m°C = the thermal conductivity of plaster,
- t_{c1}= 15, 20, or 25 cm = the thickness of the roof bottom layer of concrete,
- $R_{asphalt}$ = 0.14 m^2 °C/W = the thermal resistance of the asphalt sheet,
- $t_{insulation}$ = 4 cm for insulated roofs/walls and 0 cm for uninsulated roofs/walls,
- $k_{insulation}$ = 0.03 W/m°C = the thermal conductivity of polystyrene extruded insulation sheet,
- t_{c2} = 5 cm = the thickness of the roof top layer of concrete,
- $k_{concrete}$ = 1.219 W/m °C is the thermal conductivity of concrete,
- h_{ro} = 22.72 W/m^2 °C = the roof outside heat transfer coefficient,
- h_{wi} = 8.29 W/m^2 °C = the wall inside heat transfer coefficient,
- k_{block} = 0.383 W/m °C for thermostone, 1.443 W/m °C for a hollow concrete block of the type shown in figure 2, and 0.960 W/m °C for a hollow concrete block of the type shown in figure 3,
- t_{block} = 20 cm = the thickness of one block or two blocks (for uninsulated walls only one block of thickness 20 cm is used and for insulated walls two blocks are used of thickness 10 cm each), and
- h_{wo} = 22.72 W/m°C = the wall outside heat transfer coefficient.

Some of the above property data are taken from (9), while others are taken from (11-13).The U-values for all roofs are presented in Table 2. The table shows that as the thickness of the main concrete slab increases the U-value of the roof decreases. The table also shows a significant drop in the U-values as one goes from uninsulated roofs to insulated roofs. For insulated roofs the U-value approach that required by the government of the state of Qatar. The U-values for the walls are shown in Table 3. A significant difference between the U-value of the wall built from thermostone blocks and the U-value of the wall built from hollow concrete blocks exist. There is no significant difference, however, in both values if walls are built from insulated blocks.

Table 1. Description of the Simple and Complex Spaces Used in the Computer Simulation

Spaces	Area of Roof (m^2)	Area of Walls (m^2)	Area of Windows (m^2)	Exposure
C - 1 (Majlis)	21.6	14.3 10.0 6.20	2.4 2.4 0.0	E S W
S - 2 (Dining Room)	13.6	10.5	1.8	E
S - 3 (Kitchen + Bathroom)	17.6	11.5 6.80	2.2 0.0	E N
S - 4 (Store)	2.30	4.00 5.00	0.0 0.6	E N
S - 5 (Hall)	31.0	13.7	1.8	S
S - 6 (Stairs)	13.4	6.20 7.10	0.0 0.0	N W
S - 7 (Bedroom 1 + Bath + Lobby)	30.8	13.7 17.1	2.4 2.2	S W
S - 8 (Bedroom 3)	16.8	8.10	1.8	N
S - 9 (Bedroom 2)	21.6	5.60 10.6	0 1.8	S W
S - 10 (Bath + Lobby)	8.40	6.50 10.6	0.4 1.2	N E
S - 11 (Bedroom 4)	16.8	11.2 10.6	1.8 1.8	N W

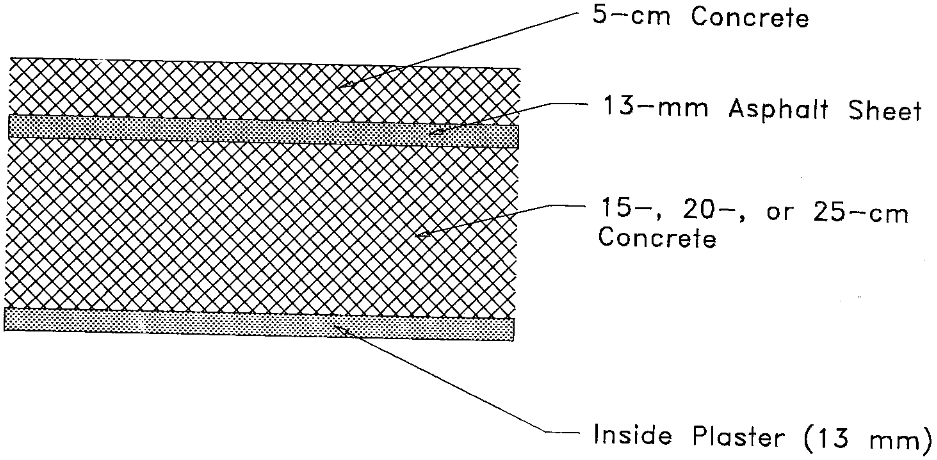

Fig. 5. Description of roof 1, 2, and 3

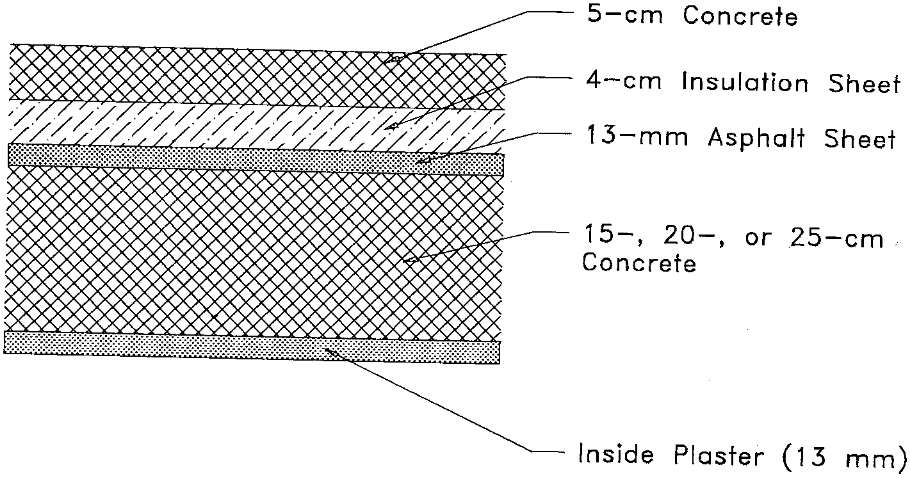

Fig. 6. Description of roof 4, 5, and 6

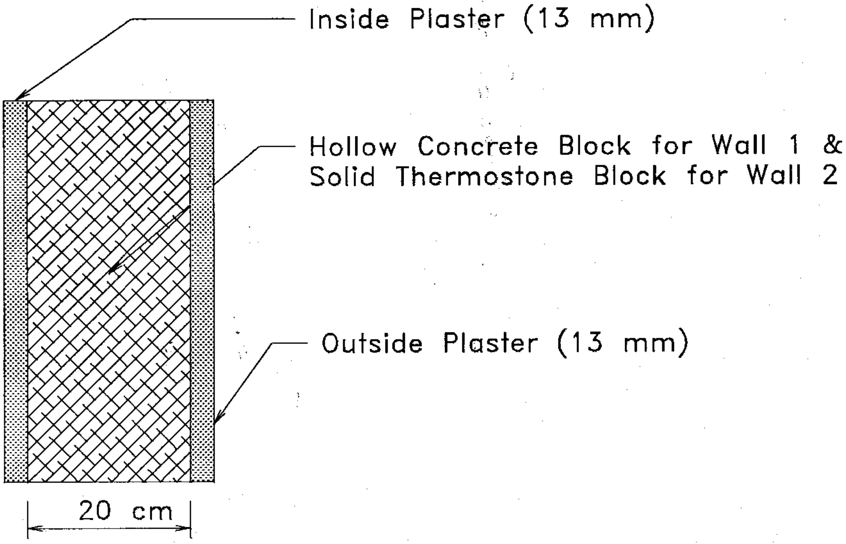

Fig. 7. Description of wall 1 and 2

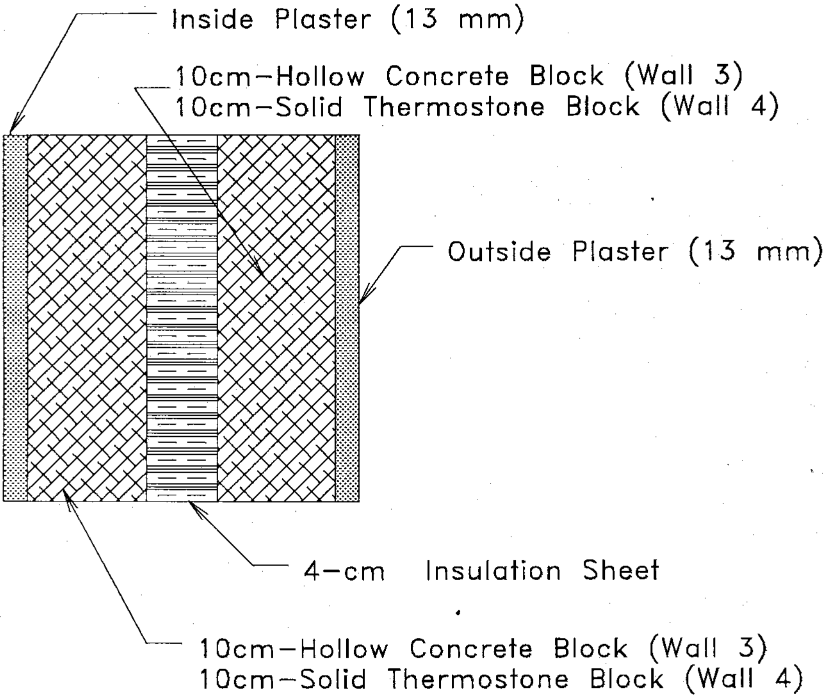

Fig. 8. Description of wall 3 and 4

Table 2. Detailed Description of the Different Type of Roofs

	Roof 1	Roof 2	Roof 3	Roof 4	Roof 5	Roof 6
Description	13 mm plaster + 15-cm concrete + 13 mm asphalt + 5 cm concrete	13 mm plaster + 20-cm concrete + 13 mm asphalt + 5 cm concrete	13 mm plaster + 25-cm concrete + 13 mm asphalt + 5 cm concrete	13 mm plaster + 15-cm concrete + 13 mm asphalt + 4-cm poly-styrene insulation + 5-cm concrete	13 mm plaster + 20-cm concrete + 13 mm asphalt + 4-cm poly-styrene insulation + 5-cm concrete	13 mm plaster + 20-cm concrete + 13 mm asphalt + 4-cm poly-styrene insulation + 5-cm concrete
U-value W/(m^2 °C)	1.896	1.759	1.641	0.537	0.526	0.515
Mass/Area (kg/m^2)	447	553	659	448	554	660

Table 3. Detailed Description of the Different Type of Walls

	Wall 1	Wall 2	Wall 3	Wall 4
Description	13 mm plaster + 20-cm hollow concrete block + 13 mm plaster	13 mm plaster + 20-cm thermostone block + 13 mm plaster	13 mm plaster + 10-cm hollow concrete block + 4-cm polystyrene insulation + 10-cm thermostone block + 13 mm plaster	13 mm plaster + 10-cm thermostone block + 4-cm polystyrene insulation + 10-cm hollow concrete block + 13 mm plaster
U-Value W/(m^2 °C)	2.967	1.390	0.575	0.487
Mass/Area (kg/m^2)	299	161	350	162

Results

Figure 9 shows the results of the study in terms of the annual electrical energy consumed for air-conditioning the model house for the different combinations of walls and roofs. For the A/C system, an average COP of 2.2 has been assumed. The maximum energy consumed is for Roof 1 with Wall 1 and the minimum energy consumed is for Roof 6 with Wall 4. The figure also shows that uninsulated roofs have higher energy consumption than insulated roofs, and that increasing the thickness of the roof does not yield any significant reduction in energy consumption whether the roof is insulated or not. For any given roof, Wall 1 which is made of hollow concrete blocks leads to a higher energy consumption than Wall 2 which is made of thermostone blocks. A wall made of thermostone blocks (Wall 2) can reduce the annual energy consumption by 25% to 30% as compared to a wall made of hollow concrete blocks (Wall 1) depending on the kind of roof used. When both walls are insulated as in Wall 3 and 4, there is no significant difference between the energy consumed for each wall.

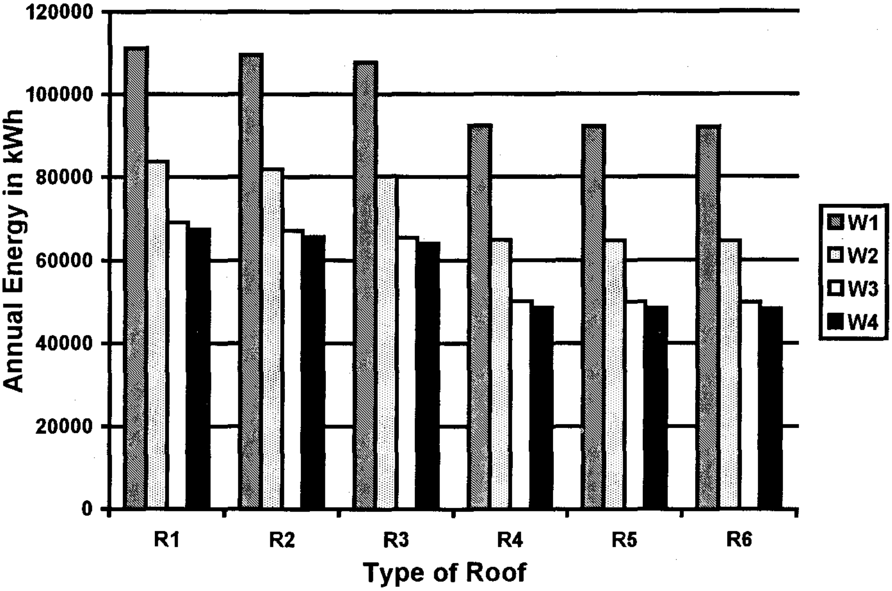

Fig. 9. Annual electrical energy consumed for air-conditioning the model house for the different combinations of walls (W) and roofs (R)

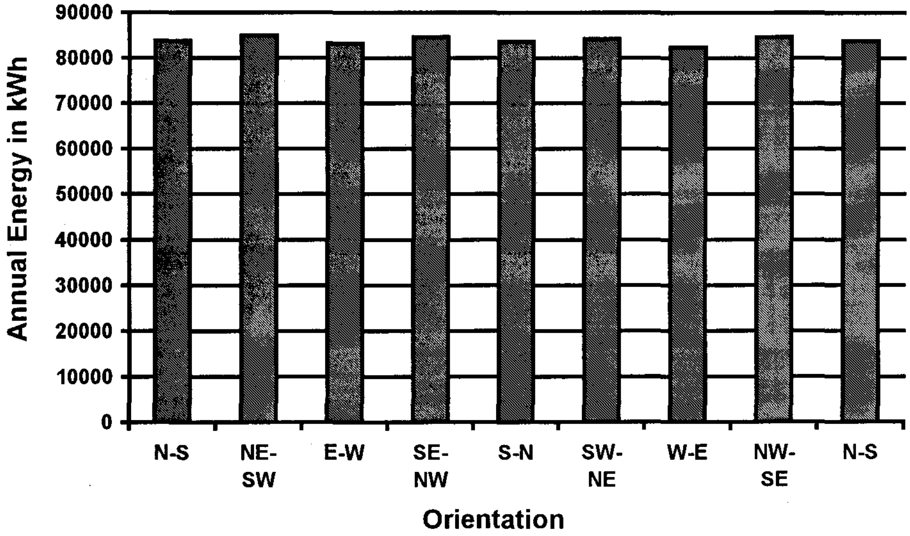

Fig. 10. Annual electrical energy consumed for air-conditioning the model house versus orientation for roof 4 with wall 2

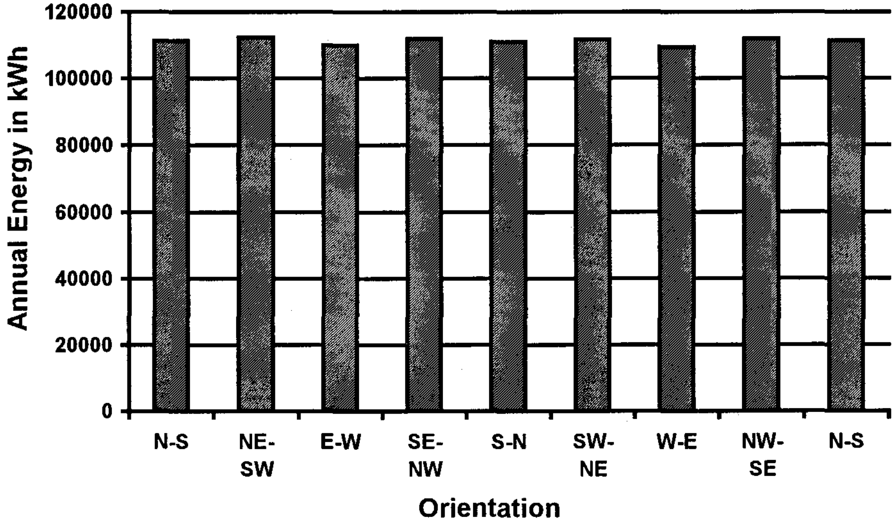

Fig. 11. Annual electrical energy consumed for air-conditioning the model house versus orientation for roof 4 and wall 1

We have also calculated the annual cooling load (and consequently the electrical energy consumed for air-conditioning the model house) for Roof 4 with Wall 1 and Roof 4 with Wall 2 for different orientations of the model house. The results for Wall 2 (Thermostone Wall) with Roof 4 are presented in figure 10 and those for Wall 1 (Concrete Wall) with Roof 4 are presented in figure 11. Both figures show that the orientation with the least annual energy consumption is the West-East orientation, although the saving is quite small and amounts to about 1.6%. Note that all the calculation presented in figure 9 are done for a North-South orientation and all the economic analysis that will follow is done for this case also.

ECONOMIC ANALYSIS

Cost Analysis

We have conducted a cost analysis to determine which of the 24 combinations has the minimum cost. The cost analysis has been conducted with the following considerations:

- The foundation and columns of the model house are the same for all combinations of roofs and walls.
- The initial cost of the house is limited to the cost of blocks for outer walls, cost of concrete for roofs, and cost of insulation.
- The cost of electricity over 35 years is reduced to an initial payment using the Present Worth Method.
- The interest rate = 6%.
- The price of electricity = Qatari Rial (QR) 0.06/kWh for 1st 4000 kWh and QR 0.08/kWh for over 4000 kWh consumed during a period of one month.
- Price of one hollow concrete block = QR 1.30.
- Price of one solid thermostone block = QR 5.38.
- Price of concrete roofing = QR 230.00/m^3.
- Price of 4-cm insulation sheet = QR 20.00 /m^2

Results

Figure 12 presents the initial cost of the house for the different combinations of roofs and walls. The initial cost is limited to the cost of the blocks of outside walls, the cost of insulation, and cost of concrete roofing. The figure shows that the lowest cost is for Roof 1 and Wall 1 and the highest cost is for Roof 6 and Wall 4. So it is clear that a concrete wall without insulation is less costly than a thermostone wall without insulation. Figure 13 presents the annual cost of electrical energy consumed to air-condition the model house for the different combinations of roofs and walls. The minimum cost is for Roof 6 and Wall 4 combination, which has the highest initial cost. The maximum cost is for Roof 1 and Wall 1 combination, which has the minimum initial cost. Also for each kind of roof, the electrical energy consumption decreases as we go from Wall 1 to Wall 4 while the initial cost increases as we go from Wall 1 to Wall 4. The figure also indicates that a thermostone wall (Wall 2) can reduce the annual energy cost by 28% to 34% as compared to a concrete wall (Wall 1) depending on the kind of roof used. The present worth of the cost of energy consumed for cooling the model house for 35 years for the different combinations are presented in figure 14 for 0% annual escalation rate in the price of electricity and in figure 15 for 1.5% annual escalation rate in the price of electricity. We see no major qualitative difference between the two results.

Figures 16 present the present worth of the total cost of the house for the different combinations of walls and roofs for 0% annual escalation rate in the price of electricity. The present worth of the total cost equals the present worth of the cost of cooling energy for 35 years plus the initial cost of the model house. The combination having the minimum present worth of the total cost is Wall 4 with Roof 4. Also for any given wall, Roof 4 leads to the minimum present worth of the total cost. Therefore, Roof 4 seems to be the most economical. For Roof 4, simple calculations show that a thermostone wall (Wall 2) can lead to 25% reduction in the present worth of the total cost as compared to a hollow concrete wall (Wall 1). When walls are insulated, the figure shows no major difference between the present worth of the total cost for a thermostone wall and a concrete wall. The same results hold for 1.5% annual escalation rate in the price of electricity, and are shown in figure 17.

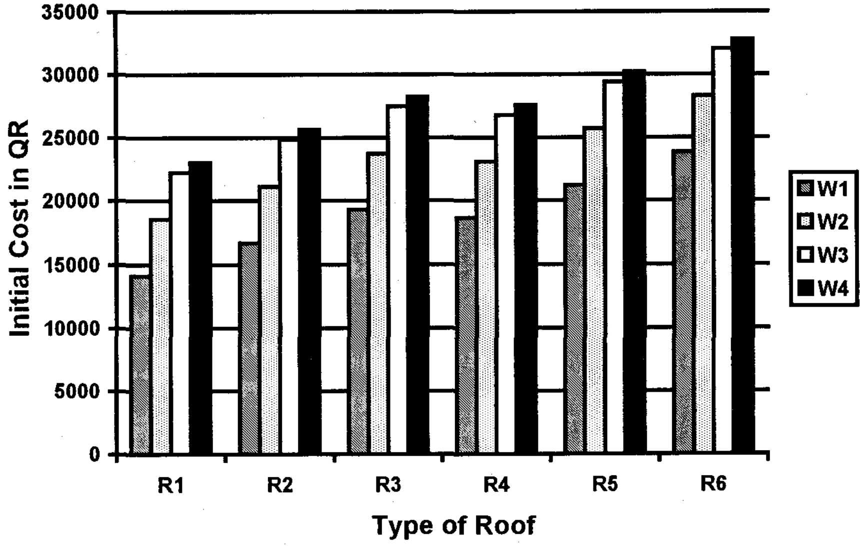

Fig. 12. Initial cost of the model house for the different combinations of walls (W) and roofs (R)

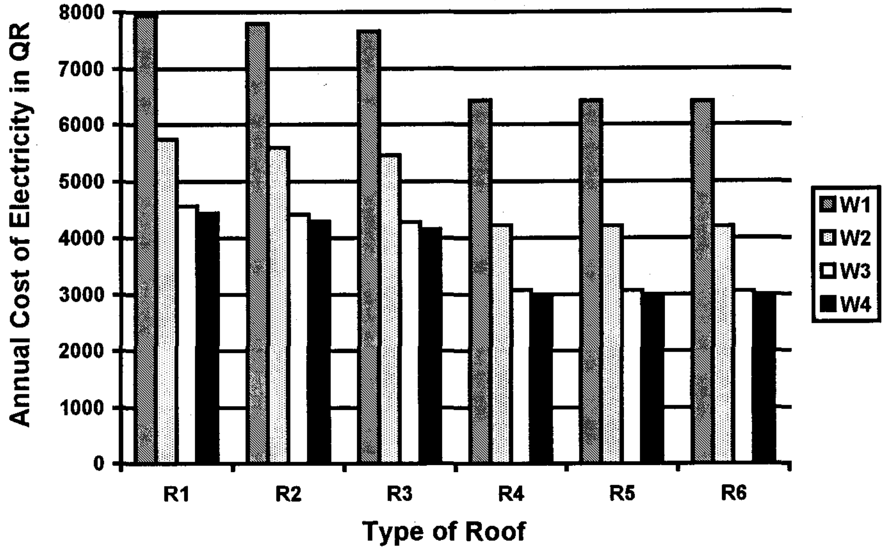

Fig. 13. Annual cost of electricity for air-conditioning the model house for the different combinations of walls (W) and roofs (R)

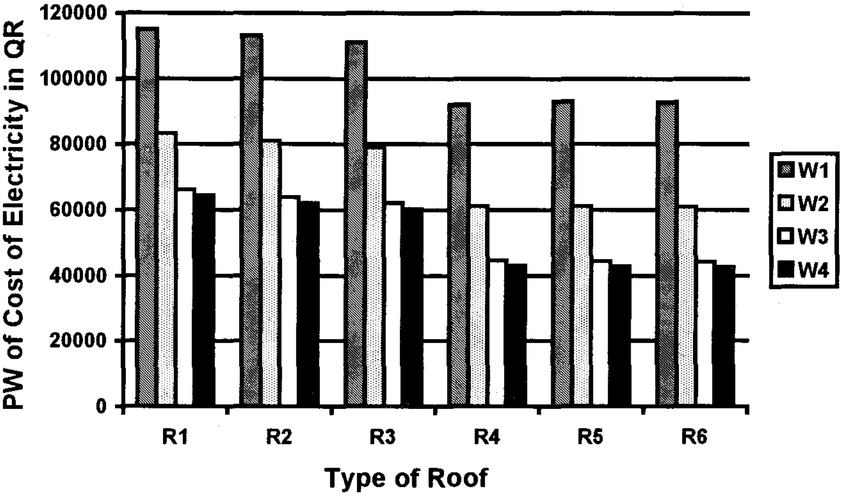

Fig. 14. Present worth of cost of electricity for air-conditioning the model house without increase in the price of electricity for the different type of walls (W) and roofs (R)

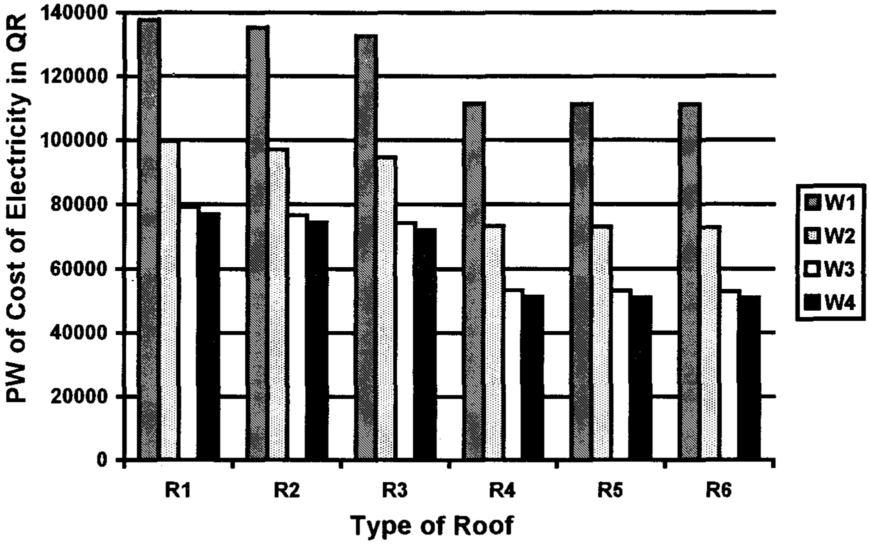

Fig. 15. Present worth of cost of electricity for air-conditioning the model house with 1.5% annual increase in the price of electricity for the different type of walls (W) and roofs (R)

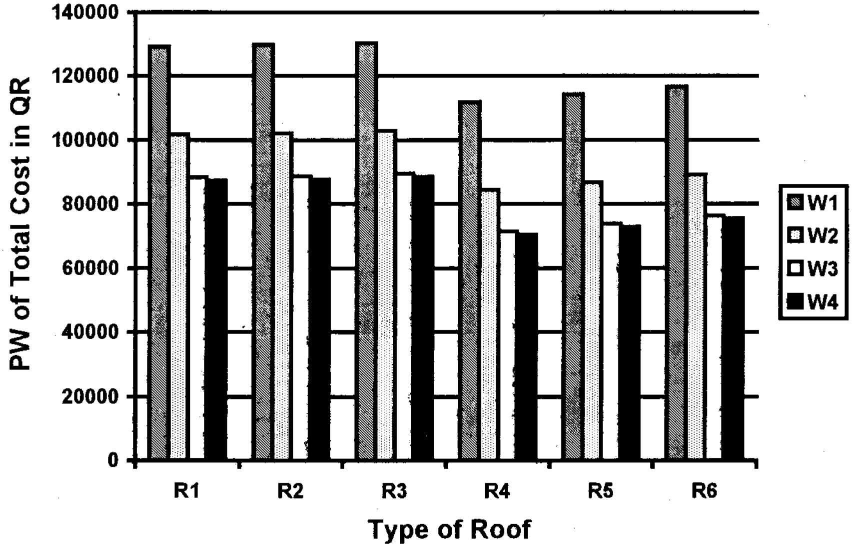

Fig. 16. Present worth of total cost of the model house with no increase in the price of electricity for the different type of walls (W) and roofs (R)

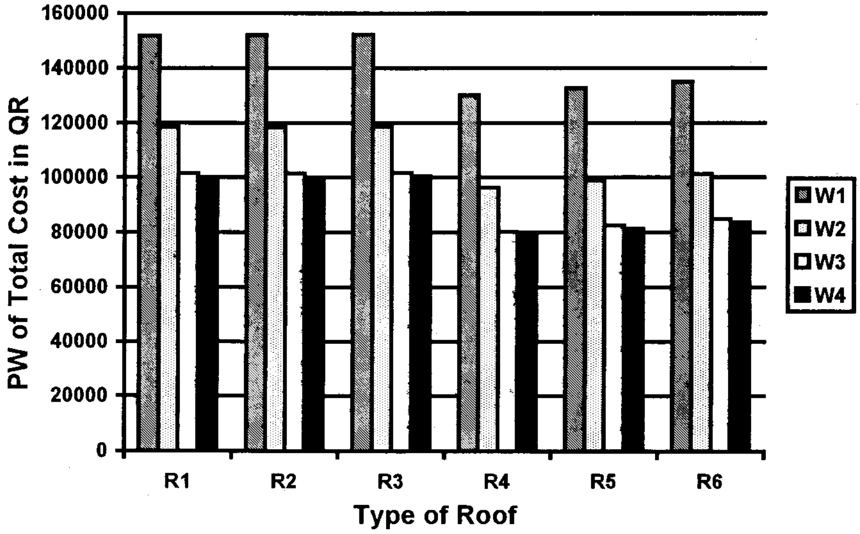

Fig. 17. Present worth of total cost of the model house with 1.5% annual increase in the price of electricity for the different type of walls (W) and roofs (R)

CONCLUSIONS

We have used the Carrier Advanced Cooling Load Program (E20-II) to estimate the annual energy consumed for air-conditioning a model house in Qatar. We have estimated the annual energy consumed for 24 combinations of 6 roofs and 4 walls. We have estimated the cost of walls and roofs for the 24 combinations. We have estimated the present worth of the cost of cooling energy consumed for 35 years with and without escalation rate of the price of electricity. The most economical roof is an insulated roof which is Roof 4. For minimum total cost, the walls and the roof of the model house must be insulated, and it does not make that much of a difference which block is used. However, if walls are not insulated, it is economical to build with thermostone blocks. Thermostone blocks offer a saving of 25% in total cost as compared to hollow concrete blocks.

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