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IMPACT OF CONSTRUCTION MATERIALS IN THE ENERGY CONSUMPTION IN HOMES IN THE CARIBBEAN

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ABSTRACT

This investigation presents the thermal analysis of an experimental, low energy consuming home for low-income families, located in Puerto Rico, where the prevailing climate is hot and humid. The objective of this analysis is to aid in the design of energy efficient homes, which in turn will reduce energy consumption in the Island. This investigation compares the analysis of this experimental house, specifically designed for the tropics, to a similarly sized, conventionally built low-cost home. Different construction materials are evaluated in conjunction with the use of either natural ventilation or air conditioning. The impact of natural ventilation is analyzed, with results for the inside temperature and interior heat removal presented and compared. Additional energy saving strategies are evaluated, including solar thermal energy for domestic hot water production, daylighting and the use of energy efficient lights. The annual energy consumption of the proposed experimental home is calculated and compared with the energy consumption of the conventional house.

The thermal load of the house is calculated through the use of mathematical simulations of the dynamic annual cooling load using well-known software such as Energy-Plus for a TMY for San Juan, Puerto Rico.

Results for the inside temperature of the experimental house, the heat loss due to natural ventilation, the cooling load when air conditioning is used, and energy consumption are presented and compared with the conventional house. Results indicate that the experimental house is 30% more energy efficient when all the energy saving strategies are considered.

1. INTRODUCTION

In Puerto Rico, the development and construction of single-family homes is one, if not the largest business in the Island. The pace of new construction is close to 20,000 units per year for the last five years as shown in Figure 1. This situation is further impacted by the fact that reaching comfort levels in typical homes is a challenging task given the nature of the hot and humid climate of the subtropics. This fact is clearly evidenced by the high net energy consumption in the residential sector that is reaching 35% of the total energy produced today in the Island, which has a capacity close to 3 GW. Furthermore, Puerto Rico produces all its electricity from imported oil, coal, or natural gas, resulting in a high electrical rate (more than $0.12/kWh). Therefore, the development of low energy consuming housing is of high priority in the Island. However, conventional home construction is poorly conceived in terms of energy efficiency, as most homes are built of conventional poured-in-place concrete with flat roofs.

This analysis of an energy efficient single-family house will help develop design strategies for low cost, contemporary architectural solutions with quality interior and exterior spaces that will be at least 30% more energy efficient than equivalent homes. The few local energy conserving buildings from the recent past (last 20 to 30 years) have been the result of poorly conceived architectural solutions with inappropriately integrated solar technology, mostly domestic solar water heaters.

We propose here the analysis of an experimental architectural and energy efficient single-family house to help reduce the consumption of conventional energy on the island. The scheme is being developed by an interdisciplinary group of research engineers, and

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architects contracted by the Housing Department of Puerto Rico, as described in following pages.

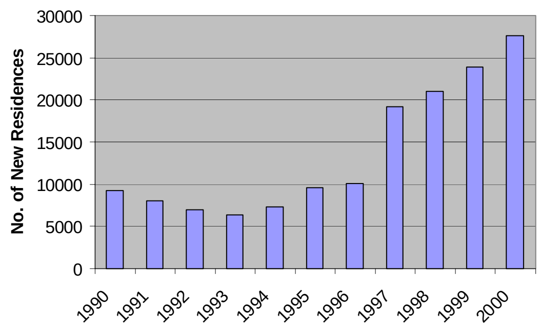

Figure 1: Annual Growth of New Residences in Puerto Rico[1] 1990-2000

To reach the goal of suggesting strategies that will lead to reducing residential energy consumption in significant ways, the design of energy efficient homes must be conducted using adequate analytical tools that permit the analysis of construction materials and the use of systems such as domestic solar hot water. We employed Energy Plus, a sophisticated software that allows for dynamically simulating the thermal performance of a house interacting with the surroundings in a given location and to modify the characteristics of construction elements including walls, roof, and windows, in order to evaluate the resulting indoor temperature. Two different cooling scenarios were investigated, namely the use of natural ventilation and the use of active air conditioning system.

2. BACKGROUND

One of the most challenging tasks of the present work is to establish an objective comparison for the use of natural ventilation vs. mechanical cooling. This problem has been recently started to be addressed by ASHRAE, which is proposing a modification of Standard 55, Thermal Environmental Conditions for Human Occupancy, to now include a more adaptive field-based alternative for application to naturally ventilated buildings [1]. This analysis revealed that occupants of centralized HVAC buildings were twice as sensitive to deviations in temperature as were occupants of naturally ventilated buildings. The acceptable range of indoor operative temperatures for a naturally ventilated building can be determined from Figure 2 below by knowing the average of the mean minimum and maximum air temperatures for a given month. During the design phase of a building, these numbers could be compared to the output of a thermal simulation model of the proposed building to determine whether the predicted indoor temperatures are likely to be comfortable using natural ventilation, or if air conditioning would be required [1].

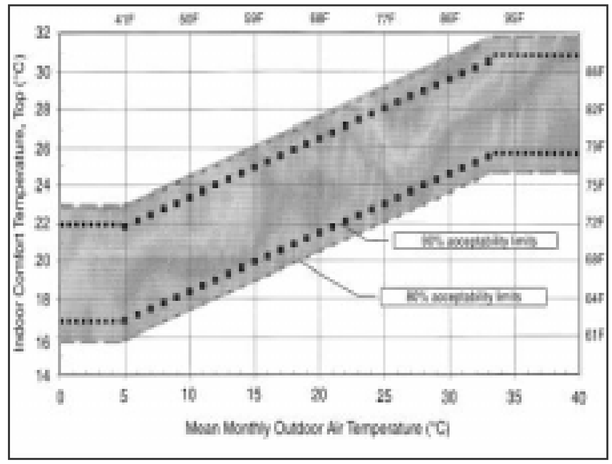

Figure 2: Adaptive Standard for Naturally Ventilated Buildings [1].

The thermal and ventilation performance of a naturally ventilated ecological house in Helsinki, Finland, was studied by Simonson [2]. The consumption of total primary energy and space heating energy were measured to be 30% less and 36% less than in typical Finnish houses, respectively.

Experimental results for the use of a new prototype of horizontal hollow concrete block for the construction of houses in Thailand was conducted by Khedari et al. [3]. Thailand has a tropical climate similar to Puerto Rico. Performances were compared using two small houses (1.2 m x 1.2 m x 2 m) one of them included two rows of the new prototype located near the ceiling and floor in all windows. The results showed that with closed windows the average room temperature of the house with the new prototype block was about 2 to 3 ^{o}C lower than the house without this block. The difference is about 0.5 to 1 ^{o}C with opened windows.

A study of different strategies for naturally ventilated office buildings was conducted by Gratia et al. [4] for climates like Belgium. The author mentioned that for northern European climates, natural ventilation can be considered for cooling loads in the range of 10 to 35 W/m^2 and for this case air conditioning system will not be necessary. As a conclusion the author mentioned that night cross ventilation and single-sided night ventilation are almost as effective, both reducing cooling needs by about 40%.

3. DESCRIPTION OF SIMULATION

Two houses were used for the simulations:

[1] Source: Puerto Rico Planning Board.

1) A experimental house with non-conventional materials (Non Conventional house).
2) A conventional house with conventional materials (Base house).

The strategy followed for the thermal simulation is shown in Figure 3 where two variables were monitored to account for efficiency: the *Indoor Temperature* of the house for the case when natural ventilation is used and the *Cooling Load* for the case when air conditioning is used. For the case when natural ventilation was considered as a cooling mechanism, blinds were used for the windows. No blinds were used when air conditioning was simulated to cool the Non Typical house.

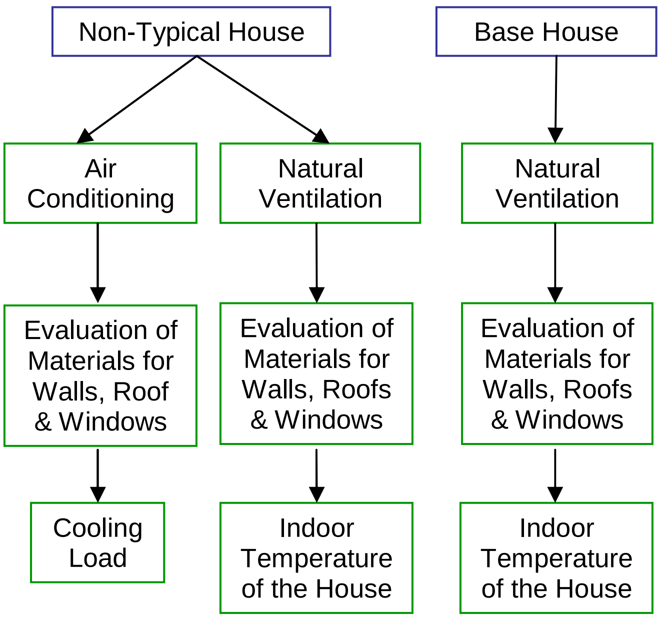

Figure 3: Strategy for the Evaluation of Construction Materials.

The strategy followed for the calculation of the energy consumption is shown in Figure 4 for the two cases considered. For the experimental, non-typical house a domestic solar water heater was considered to supply hot water as well as fluorescent lights and for the base house an electric water heater was considered and incandescent lights. The number of people considered was 3 for each house.

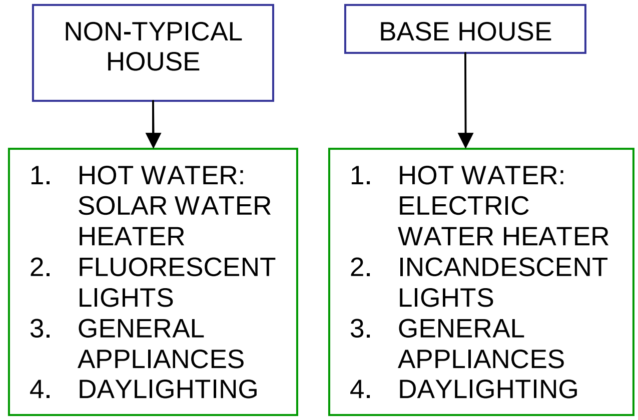

Figure 4: Strategy for the Evaluation of the Energy Consumption.

The same electrical appliances were considered for both cases along with the use of daylighting.

3.1. Non-typical House

This house has the same area and distribution corresponding to a conventional house for low-income families in Puerto Rico, but incorporates an innovative design for the walls, roof and windows with the intention of allowing for maximum natural ventilation. Figure 5 shows the layout of this house as was used for the simulation.

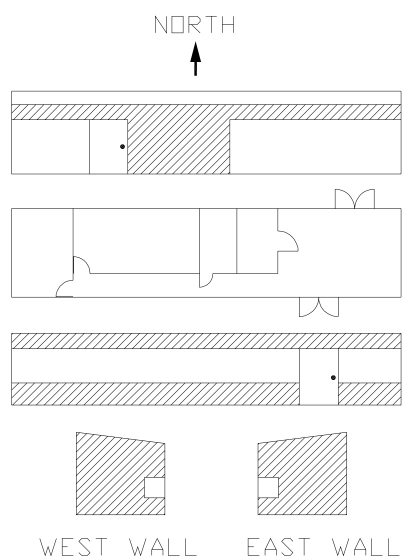

Figure 5: Non-Typical House Used in the Simulation. (From top to bottom: south elevation, floor plan, north elevation, west and east elevations)

The main characteristics of this experimental, non-conventional house are:

- Area: 70 m^2

- Tilted roof (20^{o}) facing south
- Long axis in east-west orientation
- Large window's area to facilitate natural ventilation, about 60% of floor area.
- All windows with blinds.

The materials suggested for the non-typical house are listed below and were chosen to supply insulation and a small thermal mass to avoid heat storage and are identified as Case A in Table 1:

Walls:
- Aluminum corrugated 0.001565 m (1/16 inch).
- 0.0127 m (½ inch) oriented strand board on 2 x 4 studs.
- 0.0889 m (3 ½ inch) perlite insulation.
- 0.0127 m (½ inch) gypsum board.

Roof:
- Aluminum corrugated 0.001565 m (1/16 inch)..
- 0.0889 m (3 ½ inch) rigid polystyrene insulation.
- 0.0127 m (½ inch) oriented strand board.

Glass: 0.003 m clear.

In warm humid zones, large openings are needed for cross-ventilation and blinds can be used to obstruct direct light and to reflect light from the ground [5]. Blinds are used for windows for the non-typical house.

The software package used for the simulation is Energy Plus and the location is San Juan, Puerto Rico. The materials [6] used in the simulation are presented as the different cases considered and are shown in the Table 1 below.

Simulations were conducted considering the different materials listed in Table 1 and for two conditions: natural ventilation and mechanical air conditioning. For natural ventilation the inside temperature of the house is monitored and the amount of heat removed from or added to the house is presented as a measure of the natural ventilation effectiveness. Air conditioning was used to evaluate the thermal performance of the construction materials obtaining the corresponding cooling load for the house. No blinds were considered for this case and a reflective glass was simulated as Case G for air conditioning only.

3.2. The Base House

A base case is used to compare the energy consumption and the inside temperature when natural ventilation is used to cool the house, with the energy consumption and the inside temperature of the non-typical house using the non-conventional materials as listed in Case A, Table 1. The base case is a typical house for low-income families in Puerto Rico with a floor area of around 67 m^2 and a distribution as shown in Figure 6. The construction materials for the Base Case are conventional materials and are those in Case C, Table 1. Similar rates as the used for the non-typical house were used for energy consumption due lighting and appliances for the base house.

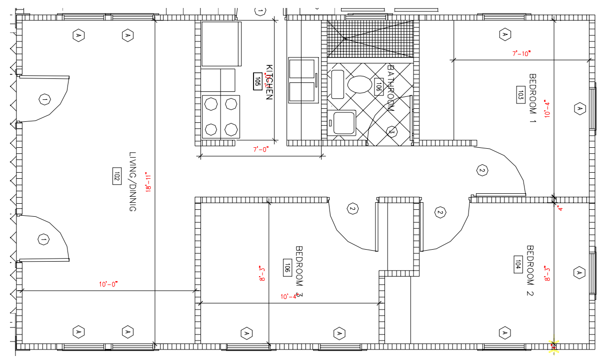

Figure 6: Typical House for Low-Income Families, PR.

3.3. Materials

A list of the materials used in the simulation is shown in Table 1 below. These materials were selected because can be available in Puerto Rico.

Table 1: Materials Used in the Simulation.

CASE	Material for Walls	Material for Roof	Glass
A[1]	South & North Walls: - Aluminum corrugated 0.001565 m (1/16 inch). - 0.0127 m (½ inch) oriented strand board on 2 x 4 studs. - 0.0889 m (3 ½ inch) perlite insulation, R: 1.9 m-K/W. - 0.0127 m (½ inch) gypsum board. East & West Walls: - 0.2032 m (8 inch) concrete block.	- Aluminum corrugated 0.001565 m (1/16 inch).. - 0.0889 m (3 ½ inch) rigid polystyrene insulation, 0.03 W/m K . - 0.0127 m (½ inch) oriented strand board.	3 mm Clear
B[2]	- 0.0508 m (2 inch) concrete. - 0.0508 m (2 inch) polystyre-ne 0.03 W/m K.	- 0.0508 m (2 inch) concrete. - 0.0508 m (2 inch) polystyre-ne, 0.03 W/m K.	3 mm Clear

	- 0.0508 m (2 inch) concrete.	- 0.0508 m (2 inch) concrete.	
C	- 0.2032 m (8 inch) concrete block	- 0.1016 m (4 inch) concrete.	3 mm Clear
D	- 0.0254 m (1 inch) insulation outside, 0.04 W/m K. - 0.2032 m (8 inch) concrete block.	- 0.0254 m (1 inch) insulation outside, 0.04 W/m K. - 0.1016 m (4 inch) concrete.	3 mm Clear
E	- 0.2032 m (8 inch) concrete block. - 0.0254 m (1 inch) insulation inside, 0.04 W/m K.	- 0.2032 m (8 inch) concrete block. - 0.0254 m (1 inch) insulation inside, 0.04 W/m K.	3 mm Clear
F	- 0.0254 m (1 inch) wood.	- 0.0254 m (1 inch) wood.	3 mm Clear
G	South & North Walls: - Aluminum corrugated 0.001565 m (1/16 inch). - 0.0127 m (½ inch) oriented strand board on 2 x 4 studs. - 0.0889 m (3 ½ inch) perlite insulation, 1.9 m-K/W. - 0.0127 m (½ inch) gypsum board. East & West Walls: - 0.2032 m (8 inch) concrete block.	- Aluminum corrugated 0.001565 m (1/16 inch).. - 0.0889 m (3 ½ inch) rigid polystyrene insulation, 0.03 W/m K. - 0.0127 m (½ inch) oriented strand board.	6 mm Reflective & No Blinds

(1) Non-Typical House materials.
(2) Material similar to Concretek^T.M.^.

The case C has the typical materials used in the construction of houses in Puerto Rico. All other materials can be considered non conventional materials or modifications to the case of typical materials.

Cases D and E were suggested as variations of the Case C to evaluate the effect of using insulation inside and outside the concrete block wall.

Case G was considered to see the effect of using reflective glass when air-conditioning is used for cooling the house.

3.4. Energy Calculations

For energy calculations two cases were considered: one without air-conditioning and one with air-conditioning. The next classifications were considered in the simulation:

Case I:
- Hot water.
- Lights
- Appliances

Case II:
- Hot water.
- Lights
- Appliances
- Air-conditioning

In relation to hot water, a solar water heater including an electrical heater in the storage tank was considered to supply the energy needed for this application. The rate of energy consumption to heat water was considered as 23.9 GJoules per year [7] which is the average household energy consumption for water heating in the USA for a total of 3 to 5 persons per house.

For the lighting, a power density of 7.18 W/m^2 was considered. As a reference, the recommended power density for an office is 20 W/m^2 [8], however fluorescent lamps were considered for lighting and compared with incandescent lamps to account for the energy savings. A fluorescent light can be 3 times as efficient as incandescent lighting [9].

Related to the appliances, the rate of energy consumption considered was 32 GJoules per year [7] that is the average household energy consumption for appliances in the USA for a total of 3 to 5 persons per house.

For the air-conditioning equipment, an EER of 12 with a COP of 3.5 was considered for the energy calculations [10].

4. RESULTS

Results for the inside temperature of the experimental, non-typical house for the months of January and July and for location San Juan, Puerto Rico, are presented in Figure 7 and 8. The different materials used for the simulations were shown in Table 1 above. A similar trend is observed for the months of January and July for all cases. Case F shows the highest temperatures in the morning and the lowest temperatures at night. This can be explained because of the low specific heat of wood.

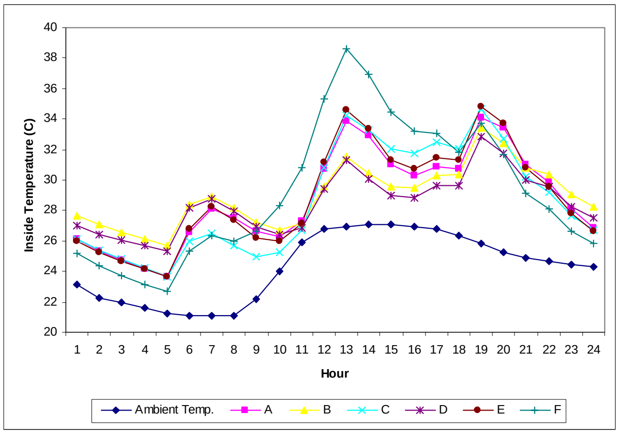

Figure 7: Month of January.

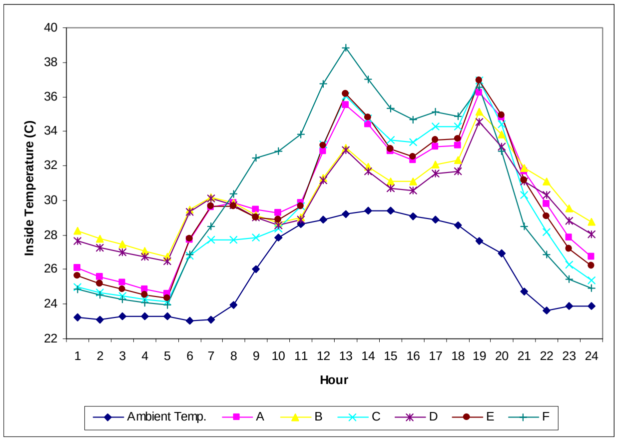

Figure 8: Month of July.

Case B and D show the lowest temperatures in the morning, but the highest temperatures at night, which could be due to the use of insulation and concrete. The concrete stores the heat in the morning and releases the heat in the afternoon. The insulation changes the heat transfer rate through the walls and traps part of the heat inside the house.

Cases A and E have similar behavior when used as construction materials for the non-typical house, approaching the results of Case F at night but showing lower temperatures in the morning. Case C shows higher inside temperatures than Cases A and E in the afternoon when used as construction materials for the non-typical house that and lower temperatures for the rest of the day.

All cases reach the lowest temperature of the day at 5:00 a.m. and the highest temperature at 1:00 p.m. while at 7:00 pm occur a peak temperature for all cases as well.

The inside temperature for the non-typical house with non-conventional materials, Case A, is compared against the base case (the typical house) and the results are shown in Figure 9 for the month of January and in Figure 10 for the month of July and location San Juan, Puerto Rico. As can be seen the non-typical house with non-conventional materials corresponding to Case A presents lower temperatures than the base case when natural ventilation is used to cool the house.

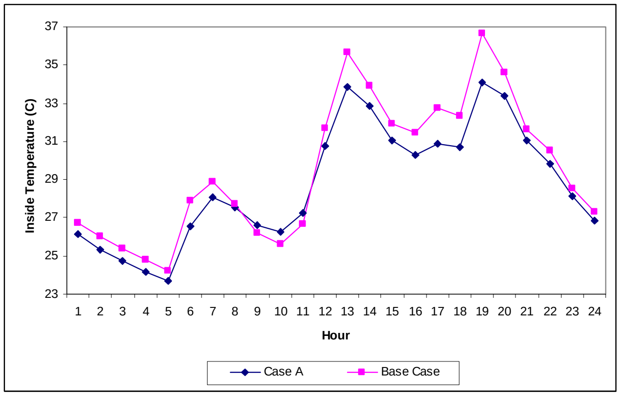

Figure 9: Inside Temperature for Month January.

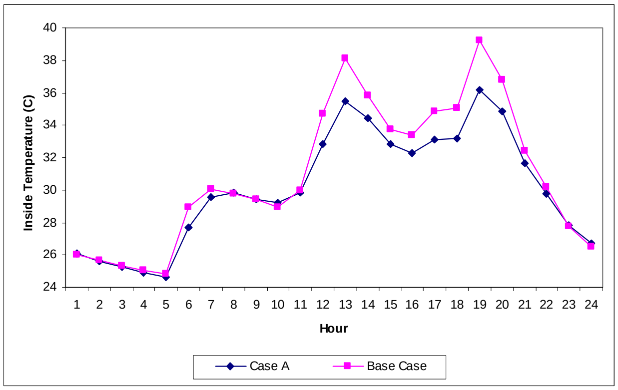

Figure 10: Inside Temperature for Month July.

Annual sensible heat loss from the house and annual sensible heat gain to the house due to natural ventilation was calculated for the non-typical house with non-conventional construction materials. The annual heat loss from the house is shown in Figure 11 and the annual heat gain to the house is shown in Figure 12.

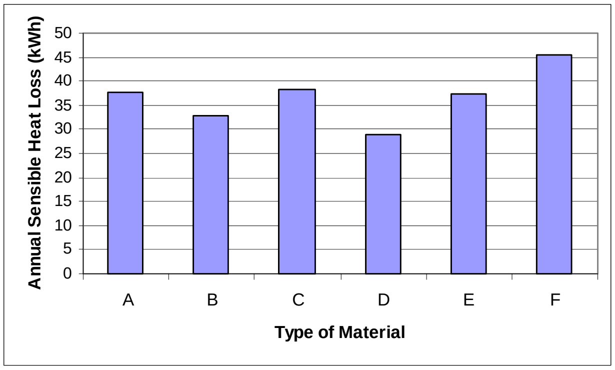

Figure 11: Annual Heat Loss due to Natural Ventilation.

As shown in Figure 11, the highest annual heat loss due to natural ventilation is for the Case F and the lowest heat loss is for the Case D. In Figure 12 it can be seen that Case A has almost no heat gain due to the natural ventilation, however it must be mentioned that the heat gain due to natural ventilation is relatively small in respect to the heat loss.

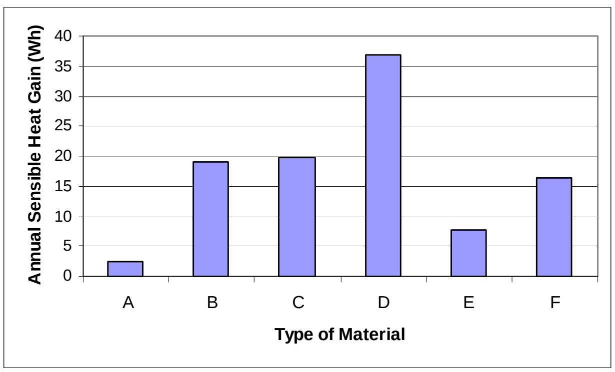

Figure 12: Heat Gain due to Natural Ventilation.

The next set of results was obtained by considering mechanical air conditioning in the non-typical house to see the thermal behavior of the materials. No blinds were considered in this case for windows of clear glass. The materials considered are those mentioned in Table 1. Room comfort was defined as constant indoor temperature of 23°C and relative humidity of 50%.

As can be seen in Figure 13, the lowest rate for the cooling load corresponds to the Case G that uses reflective glass. Cases A, B, D and E show very similar results while Case F shows the highest result. A 26% of cooling load reduction can be reached as shown in Figure 13 for Case G that uses reflective glass in windows and materials corresponding to Case A when compared to Case C, which uses conventional materials and clear glass. Only 6% of reduction in the cooling load is reached by changing the materials for walls and roof and using clear glass, as shown in Figure 13 when comparing Cases A and C. This can be attributed to the possible fact that the house has a large window area that is equal to about 60% of the floor area.

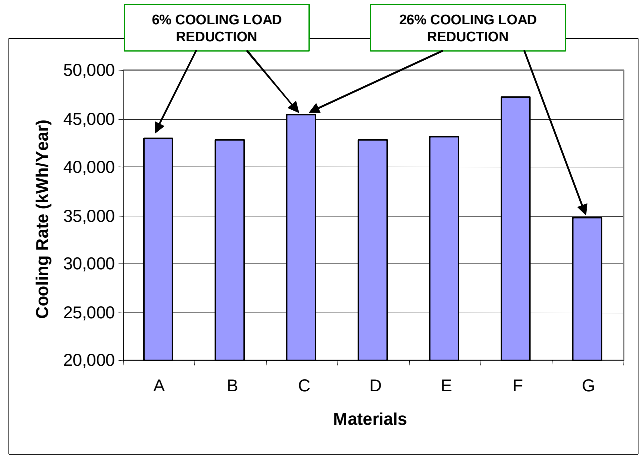

Figure 13: Annual Cooling Rate for the Non-Typical House.

Annual energy savings were calculated for the Cases I and II. Results for Case I are shown in Figures 14 and 15, correspondingly. As can be seen in Figure 14, 31.7% of annual energy savings can be reached for an annual consumption of the household appliances of 8,200 kWh which corresponds to 32 GJoules per year [7] equivalent to the average household energy consumption for appliances in USA for a total of 3 to 5 persons per house.

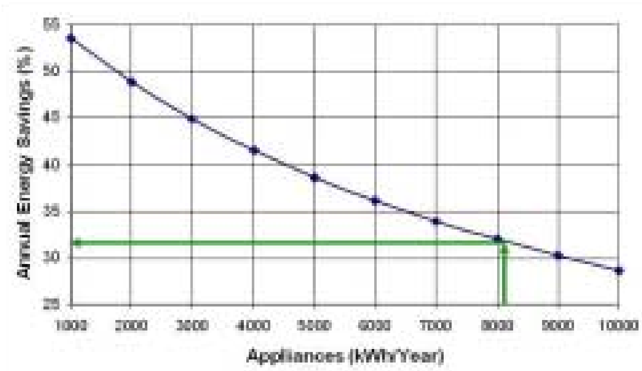

Figure 14: Annual Energy Savings with Natural Ventilation.

Figure 15 shows the energy savings breakdown for a annual energy consumption for appliances of 8,200 kWh (about 32 GJoules per year [7]) where 31.7% in energy savings is reached. The main contribution is made by the solar water heater with 21%, followed by the use of energy efficient lights with 10.5%. A small contribution is gained by daylighting for this case.

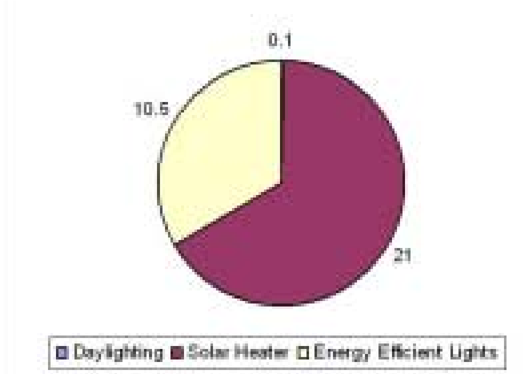

Figure 15: Energy Savings Breakdown with Natural Ventilation.

For the case when air-conditioning is considered and for the non-typical house, Case II for the energy calculations, 29.4% of annual energy savings can be achieved when comparing construction materials, or Case C vs. Case G of Table 1. Figure 16 shows the energy savings breakdown for a annual energy consumption for appliances of 8,200 kWh (about 32 GJoules per year [7]).

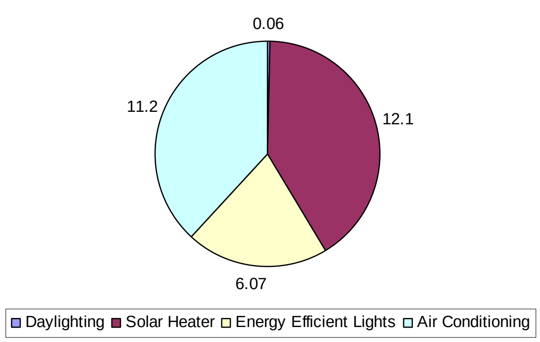

Figure 16: Energy Savings Breakdown with Air-Conditioning.

5. CONCLUSIONS

The energy consumption of two houses with floor area and architecture corresponding to typical homes located in the Caribbean has been calculated. The main differences in the houses were that one was designed to maximize natural ventilation and daylighting. In addition to the differences in architectural design, the analysis matrix considered different materials, and natural or forced ventilation and the different cases were labeled Cases A through G.

For natural ventilation, material of Case F (wood) shows the highest indoor temperatures during the day and the lowest during the night for the non-typical house.

The materials for Cases A and E show similar results for natural ventilation and when used in the non-typical house, with medium temperatures, not as hot as in Case F during the day and not as fresh as Case F during the night. Materials of Case A are wood and insulation while materials of Case E are concrete block with insulation inside.

Materials for Case B (concrete & insulation) and D (concrete block & insulation outside) show similar results when used in the non-typical house and for natural ventilation. These results show a more uniform distribution of temperatures during all day respect to other cases. These results represent a better comfort conditions in respect to the other cases presented according to Figure 2 [1].

Material of Case C (concrete block) results in higher values for the inside temperature of the house during the afternoon for the non-typical and the typical house than material of Case A and for natural ventilation.

For the case when a mechanical air conditioning was considered in the non-conventional house, it was found that the insulation of walls and roof plays an important role. A larger effect was noted when reflective glass is used because of the large window area in the non-typical house, Case G versus Case C. The reduction in cooling load ranges between 20% and 26% for the cases when no blinds are used for windows and when blinds are used respectively.

It was found that annual energy savings of 30% or more can be achieved if the energy consumption of the household appliances is limited to a maximum of 9,000 kWh/Year or less using a solar water heater and fluorescent lights for the case of natural ventilation.

The annual energy savings for the case when mechanical air-conditioning is used was found to be 29.4% for an annual energy consumption of household appliances of 8,200 kWh and when a solar water heater is used. Daylighting contributes very minimum to the overall energy savings for both cases.

ACKNOWLEDGMENTS

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