Earthen buildings for a low-cost high-energy performance social housing

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Abstract: A social housing project was carried out in a developing country (Benin, West Central Africa). A complex of twenty two-storey houses was designed in the city of Cotonou, in order to achieve the best architectural solution with the lowest cost. The project was carried out taking into account the bioclimatic and passive architectural devices in a h ot-humid climate site. By using the software ECOTECT V 5.50 the hygrothermal behavior of the buildings was assessed. Every building was supposed with a reinforced concrete structure, and unfired brick walls. The raw earth was also used as a filler layer in the floor and roof slabs. None HVAC was assumed. The simulation has led the best results in terms of thermal performances and indoor comfort conditions. A partial do-it-yourself building was also supposed in the project, allowing to bring down, with use of the earthen materials, the cost of the whole project of almost 30%.
Further investigations on the earthen materials were started at the Laboratory of Thermophysics of Materials (LTM), University of Politecnico di Bari. The aim of the study is to obtain a low-cost high-energy performance building material suitable to achieve a better hygrothermal comfort in sustainable buildings.

Keywords: *Earth, Hygrothermal behavior, Social housing*

1. Introduction

One of the most important issue in the developing countries is the very poor quality of the houses. Several people build by themselves their houses by using local available materials; producing in the most cases a very high level of indoor discomfort, moreover increasing the environmental pollution.

In terms of architectural design, a global policy attempts to invert this trend by increasing the energy efficiency of the building themselves [1].

Several authors [2,3] pointed out the importance to design a building in regards to the bioclimatic and passive architecture devices, taking into account the climate of the site besides the availability of the local resources. In the tropical climates, heat as well as moisture poses an important consideration that must be factored into design of suitable and affordable housing in such an environment [4].

It can be remarked that the temperature and the relative humidity of the indoor building environment are mainly related to the construction materials [5].

Many studies highlighted the importance of the earth, as an ancient eco-friendly building material, able to keep constant indoor temperature and relative humidity values [6,7,8,9]. Different earthen building techniques and several codes are used also in the hot-humid climate countries [10].

The main aim of the present work was to design in a developing country, Benin, an architectural complex of social affordable houses with the highest energy efficiency and the lowest economic cost. The project, started from the social and economic site analysis, has carried out following the bioclimatic and passive architecture devices and was analyzed by the software ECOTECT V 5.50.

2. Methodology

2.1. Site analysis

The work was carried out in the city of Cotonou, which belongs to the country of Benin, in Central West Africa. Before starting the project several social-economic and climatic aspects were taken into account in order to obtain a sustainable project. As refers by the lists of the UNDP [11] Benin is one of the poorest countries in the world; a study extracted by the Government of Benin [12] has demonstrated that 79,1% of the houses were built with metal sheet roofs in 2002.

According to Koppen's climate classification the city of Cotonou was characterized by a tropical wet climate. The main features of this climate are a very small annual temperature range, heavy rainfalls and wet-warm winds. During the year the average daily temperature is included between 27°C and 32°C; the relative humidity of the air is very high with frequent peaks of about 80%.

Several aspects of the prevailing winds were also taken into account: during the driest season (from November to April) the wind, named Harmattan, with direction North-East, is warm and dry. The wetter season (from April to July), instead, is characterized by the Monsoni winds; their speed can achieve 72 km/h.

2.2. Design of the residences

The project area was a popular zone of the city of Cotonou. The main objective to accomplish was to create an integrated design building form and material as a total system able to achieve the optimum indoor comfort with the best energy saving and the lowest economic cost. Twenty two-storey houses were designed. There were considered two types of residences: type A was supposed as a duplex house for two different low-income households of 4/5 people; type B was assumed as a simplex house for one medium-income household for 6 people.

Fig. 1. The project of the residences (From left to right: Urban layout; type A building; type B building)

None HVAC system was assumed in the buildings. Different passive cooling strategies were taken into account: prevailing winds and solar irradiation analysis, shape of the buildings in regard to the site climate, study of the shape of the single building respect to the whole architectural complex, set up of the internal spaces with the different functions and use of building materials suitable to keep constant indoor temperature and relative humidity values.
According to the bioclimatic architecture devices for the hot-humid climate [2] the buildings were designed along the East-West axis with a surface/volume ratio of 0,64.
All the residences were placed along North-South direction, at the sides of the area. Some "cooling corridors" were also created by using the vegetation and thus different sun path diagrams during the day were analyzed in order to study the daily percentages of shadow.

The layout of each house was built up by a starting modular grid of 6 m by 3,5 m; then some modules were staggered with the aim to produce some external cohorts which can allow to reduce the wind speed and work as sunscreens avoiding the overheating of the internal rooms. Furthermore in each building was created a central natural ventilation chimney [13] by using the stairwell; the sizes and the position of the windows were also taken into account to optimize the indoor comfort by studying the direction of the airflows.

Since the relative humidity rate was very high during the whole year, it was assumed that all the non load-bearing walls and some layers of the floor slabs and the roofs were made respectively of unfired bricks and unbaked earth layer. Several studies pointed out the good moisture buffering capacity of the loam as a building material [6,7,8,9].

3. Results

3.1. Analysis of the thermal performances

According to the EN ISO 13786 [14] the thermal transmittance (W·m^2/K), the time lag (h) and the decrement factor of the walls and the floor slabs were evaluated (tab.1-2). Every building was assumed with a reinforced concrete structure. The non-load bearing walls were supposed with an air cavity of 7 cm, two internal and external layers of earthen bricks of 15 cm covered with common plaster layers of 1,5 cm. About the floor slabs the thermo-acoustic layer were supposed of a mixture of wood shavings and raw earth. Minke pointed out the excellent thermal capacity of the unbaked earth [15].

The results showed in the tables 1 suggest that by using the unbaked earth it can be achieved a good thermal inertia; thus it was possible to keep constant values in terms of indoor temperature during all the day even if high variation of external temperature values occur.
According to the EN ISO 13788 [16] the internal moisture of the walls was also verified by using the MC4 software. It can be seen by the figure 2 that during the whole year the saturation vapor pressure (red line) was higher than the vapor pressure (blue line) in each layer of the wall. This means that none internal moisture condensation is possible.

The performance of a passive cooling system through an underground duct was estimated. According to the EN ISO 13370 [17] the average annual ground temperature was assessed at a deepness of about 1 m. It was calculated that this allows to reduce the indoor temperature in a range between 1,5°C and 7,5°C during the summer.

Table 1.Thermophysical properties.

	Surface Mass (kg/m^2)	Thermal Resistance (m^{2}K/W)	Thermal Transmittance (m^{2}K/W)	Thermal lag (h)	Decrement factor (-)
External walls	306,1	2,246	0,445	14,69	0,136
Roof slab – type B	453,3	1,991	0,502	12,94	0,102

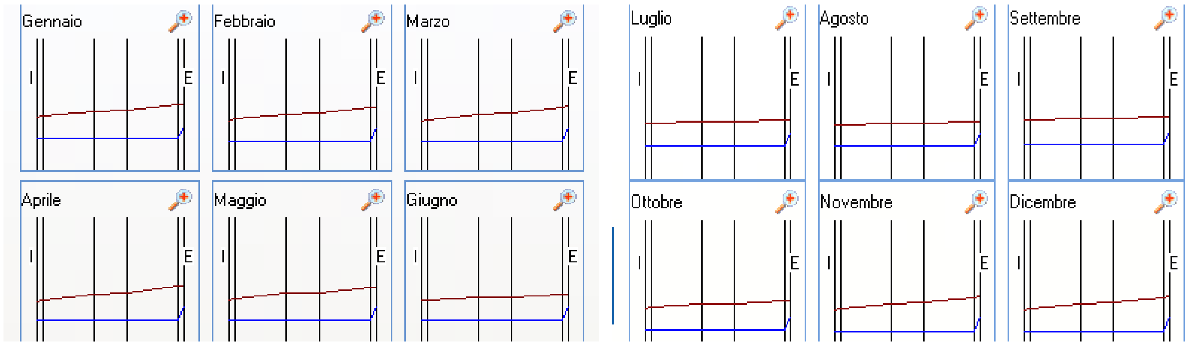


Fig. 2. Water Vapor Pressure profile in the external wall (in red the saturation vapor pressure, in blue the vapor pressure)

3.2. *Analysis of the energy performances with ECOTECT*

Both the two residences (type A and B) were assessed by the software ECOTECT V 5.50. Each type of building was supposed as a block of different "thermal zones", each of one set with specific hygrothermal and physical properties as shown in the table 2. The database, previously calculated according to the EN ISO norms, was used to carry on the simulation.

Table 2. Hygrothermal and physical properties of the zones.

	Clo value	Air relative humidity (%)	Air speed (m/s)	Illumination level (lux)	Comfort Band (°C)	Latent - sensibile heat gain (W/m^2)
Living area	0.40	60	0.5	300	18-26	2.14-0.86
Night area	0.40	60	0.5	200	18-26	2.14-0.86
Bathroom	0.20	65	0.5	200	18-26	5-2
Kitchen	0.40	65	0.5	300	18-26	5-2
Corridor	0.40	60	0.5	150	18-26	5-2

3.2.1. *Indoor temperature analysis*

The graph 3 shows the annual temperature distribution of the main internal zones. The comfort band (in yellow) was considered included in the range between 18°C and 26°C.
The temperature of the living area (in red) is in the comfort band for 70% of the hours.
Moreover in the sleeping area (in green) the temperature is in the comfort area for 79% and 89% of the hours. This condition changes in regard to the floor in which the area is.
Conversely the warmest zones of the building are the corridors, the bathrooms and the kitchen.

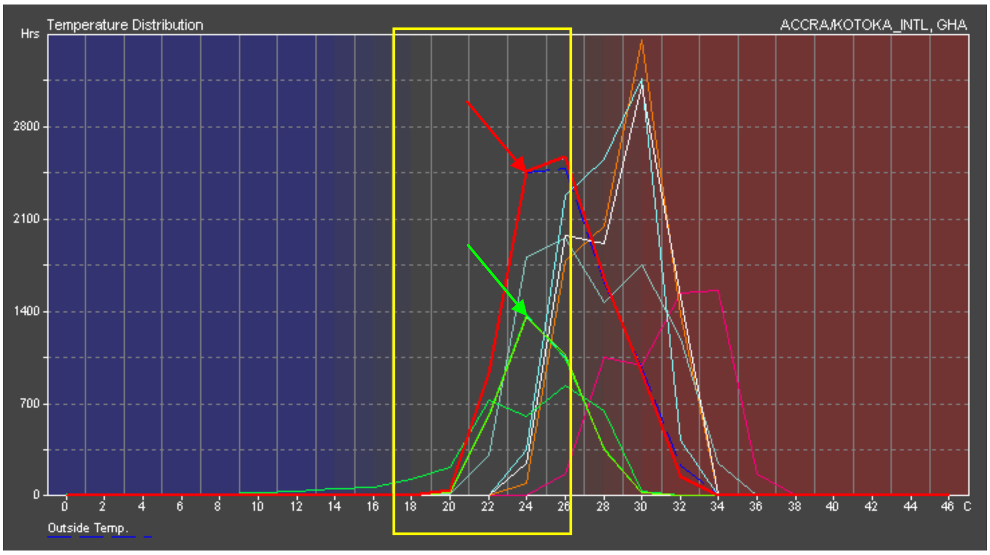


Fig. 3. Annual temperature distribution (in red the living area; in green the sleeping area, in yellow the comfort band)

3.2.2. Internal gain analysis

It was carried out, also, the annual and daily thermal gain and loss analysis due to the temperature gradient in the building.

Due to the solar radiation intensity the main daily gain, of about 1.760 Watts, was achieved during the first afternoon hours in the first and the last months, i.e the driest season of the year. In the night hours there were found the best indoor comfort conditions.

This is owing to the good thermal transmittance, the time lag and the decrement factor described above (table 1) of unfired brick walls.

3.2.3. Wind and solar radiation analysis

The passive ventilation is one of the most effective strategies to use in a hot-humid climate. This is the reason why the buildings were designed in regard to the direction and the type of the winds. The buildings were set with the direction North–South, using the opposite direction of the winds that allowed to dump the discomfort effect produced by the external relative humidity and temperature. On the other hand the design of the external cohorts could also reduce the speed of the air fluxes, when the wind speed is too high.

The design of the buildings was carried on taking into account the solar exposure. Fig. 4 shows the average daily absorbed solar radiation. It can be noticed that the roof is the part of the building mainly involved, with a value between 480 and 600 Wh/m^2. This is the reason why it was created a system of ventilate roof by an air cavity of 4 cm (type A) and a second upturned cover above the roof slab (type B).

The annual sun path diagrams were also studied in order to design the best solution in terms of passive sunscreens. The sun path diagram (Fig. 4) shows that each building is in the shady area for the most time during the whole year.

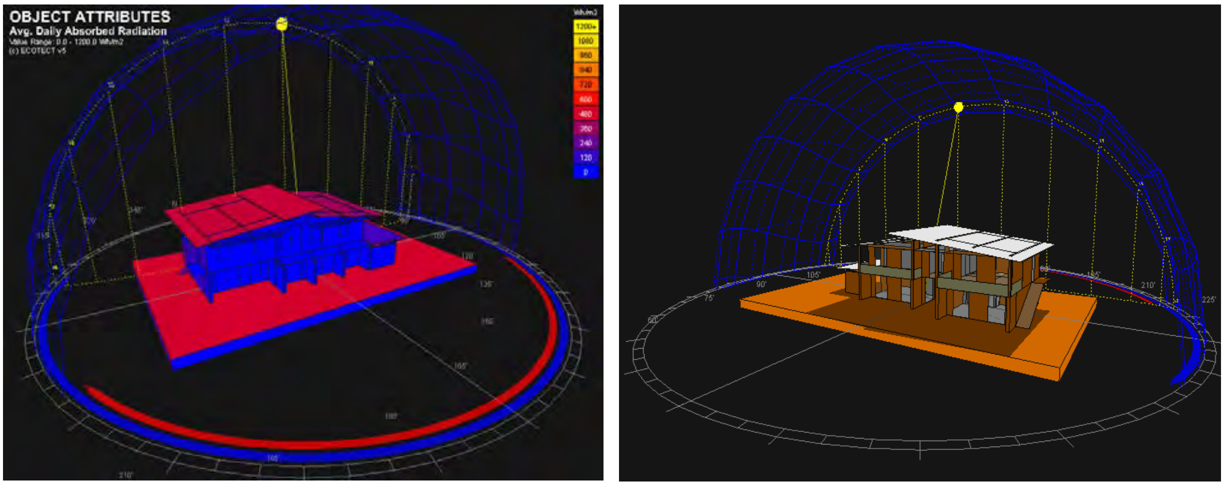
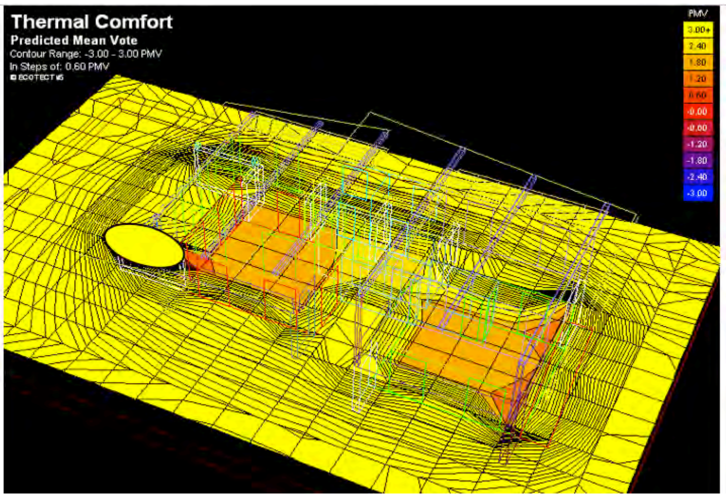


Fig. 4. Solar radiation analysis (Left: Absorbed Radiation; Right: Sun path diagram)

3.2.4. Indoor comfort analysis

According to the EN ISO 7730 [18] the PMV value (Predicted Mean Vote) was computed. The analysis was carried on considering the hottest and coldest days of the year. The graph in figure 5 refers to the warmest day of the year (April 21th) at midday. The main areas of the house, i.e the living and the night areas, show an average PMV value of 1.20. According to the software settings this value means a feeling of lightly warm.



Vote	PMV	Feeling
+3	3.00+	Very warm
Up to 2	2.40 1.80	Lightly warm
Up to1	1.20 0.60	Lightly warm
0	0.00	impartial
Up to -1	-0.60 -1.20	Lightly cold
Up to -2	-1.80 -2.40	cold
-3	-3.00	Very cold

Fig. 5. Thermal comfort – Predicted Mean Vote

3.3. Cost accounting and sustainability of the project

Several economic saving factors were taken into account in order to accomplish to low cost housing objective. The whole design of the architectural complex and the tree-shaped disposal of the buildings (fig. 1) can allow to suppose an expansion of the houses themselves in the future, solving one of the most pressing problem of a developing country: the uncontrolled population grow.

The structure of the buildings was supposed simple with a modular grid of 3,5 by 6 m. This allows to realize the housing typologies partially with do-it-yourself building, employing the future users.

In order to support the local economy, the use of many local building materials was assumed in the project. Thus it was used unbaked earth both as unfired bricks for non-load-bearing walls and as filler layer of the slabs.

A comparison between the use of fired bricks and unfired bricks was carried out; by the cost analysis it could be noticed that the unbaked earth as a building material allows to bring down the full economic cost of the project of almost 30%. As common strategy in a developing country, assuming the structure cost is at expense of the government, it was calculated that the total cost of a duplex house is about 16.900 euro and the total cost of a simplex house is about 8.500 euro at expense of the future users.

Moreover it was also calculated that with the do-it-yourself building it can be achieved a further lowering cost of about 30%; in this latter case for example the simplex house cost could be 6.000 euro at expense of the user.

4. Conclusion

The main objective of the work was to project an architectural complex of low cost houses in a developing country, characterized by a hot-humid climate. Several architectural devices and socio-economic aspects were taken into account.

The results obtained by the software analysis demonstrated that by using the unbaked earth as a building material it can be achieved a good thermal performance of the whole building envelope, in terms of thermal inertia.

Furthermore the use of many passive cooling strategies, starting from the shape of the buildings themselves up to the whole architectural configuration, have led to obtain excellent results in terms of indoor comfort.

In order to achieve a low-cost high-energy performance housing many economic strategies were also considered. Among these, the use of a local and sustainable material as unbaked earth, on the one hand, and the hypothesis of partial do-it-yourself building, on the other hand, have allowed to bring down the total housing cost of about 60% if compared with a common house built with fired bricks and traditional labor.

Several experimental investigations were started in the Laboratory of Thermophysics of Materials (LTM) (Politecnico di Bari) in order to study the hygrothermal behavior of the unbaked earth building materials.

Two different research lines are carrying on: the lightweight earth by using different additives, like straw and sawdust, and stabilized earth by the addition of the lime. The main objective of the ongoing research is to study how to optimize and obtain a sustainable building material suitable to reduce the energy consumption of the buildings with the lowest economic cost.

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