THERMAL RESPONSE TO OUTSIDE AIR TEMPERATURE AND SOLAR RADIATION OF A NBRRI MODEL HOUSE WITH A FLAT ROOF IN KANO

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ABSTRACT

The thermal response for a NBRRI model house design built in Kano has been investigated. The inner walls and roof temperatures were calculated based on a periodic theory that uses the sol-air temperature concept. Using the Fourier series the hourly temperatures of the inner wall surfaces were then obtained as a direct response to the variations of the outside air temperature and the solar radiation incident at the period. The results show that the NBRRI bricks response well to the external weather patterns. The response for the hot period showed inner surface temperatures that are generally lower than the external ambient temperatures starting from 10:00 hours to 21:00 hours, while in the cold harmattan month of January, the brick walls keep the house warm for most of the day except for the late afternoon period when the outside air temperatures are high then the inner surface temperatures are lower. Temperature swings for October and January were moderate and were between 8.5 and 11.1°C for October and between 7.7 and 9.7°C for January.

INTRODUCTION

The cost of building materials especially cement have shot up astronomically in the recent past in Nigeria. The situation is such that the provision of housing for the ever expanding population is becoming a nightmare. The situation has led to the search for alternative and cheap materials to use in building dwelling houses. The Nigerian Building and Road Research Institute (NBRRI), has been in the forefront of this research and has come out with its own type of bricks which it produces with its own making machines. These NBRRI bricks are basically made of mud (laterite) stabilized with 4% cement. Laterite or mud constitutes about 74% of the earth surface (Awad, 1988). Apart from this stated abundance another advantage of mud as a building material is that inside surface temperatures remain temperate throughout the year even in hot and dry places. The drawback of this material as a building material however are the effects of rain and wind. This however can be solved through research into proper materials engineering. This essentially is why 4% cement has been used by NBRRI for stabilizing, however more work needs to be done in this area.

In this work we examine the thermal response of a NBRRI model house built in Kano. Fig. 1 shows the floor plan of the house which consists of three bedrooms, a sitting room and adjoining dinning room, a lounge, a kitchen and a garage. An open courtyard is situated in the centre with all the bedrooms having an access to it.

MATHEMATICAL ANALYSIS

In the present work we do not consider the functional design of the building and as such the interior partitions are presumed not to have any effect. The brick walls are 140mm thick and with 10mm plastering in the inner sur-

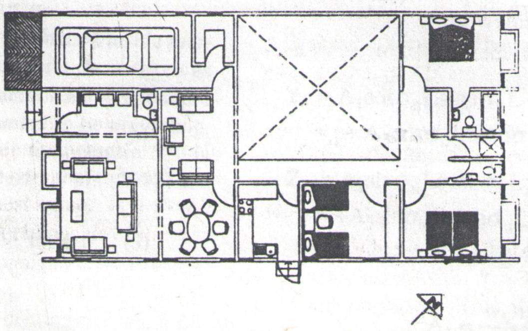

Figure 1: Floor plan of NBRRI House in Kano

face. The bricks are hold together with the plaster and this constitutes about 20% of each total wall area. Table 1 shows the total areas of walls with windows and doors.

Table 1: *Walls, windows and doors dimensions for the different directions.*

DIRECTION	TOTAL WALL AREA (m²)	TOTAL WINDOW, AREA (m²)	TOTAL OUTER DOORS AREA (m²)
NW	47.374	0.387	-
SW	32.038	2.880	5.970
SE	54.712	5.760	1.890
NE	29.008	3.960	-

The total roof area is 245.904m². In the present work we consider only a flat roof option which is constituted of a 300mm brick mixture, with a 16mm plaster underneath and also a 16mm thick asphalt as a rain proof cover at the top. In the actual building a pitched roof was used, however, we only consider here flat roof type since this is the more common type of roof found in Kano. It is hoped that in a future work the pitched roof type would be analysed. Windows are 6mm thick batten door.

The thermal analysis here presented is based on a model that combines the effects of outside air temperature and solar radiation into a single quantity which is known as the sol-air temperature T_{SA} which is calculated as:

$$T_{SA} = \frac{\alpha S}{h_{so}} + T_A + \frac{h_r}{h_{so}}(T_{SKY} - T_A) \qquad (1)$$

T_{SKY} is calculated using Swinback's (1963) relation:

$$(T_{SKY} + 273) = 0.0552(T_A + 273)^{1.5} \qquad (2)$$

The solar radiation for clear sky was obtained using Gueymard's (1989) CPCR2 computer model. The outside air temperature was obtained from actual data recorded with a Delta-T weather system for the period under consideration. Data used for the analysis were for 15th of October 1996, and 3rd January, 1997. These represent a hot and a cold period respectively. a used for the brick walls is 0.6 while a value of 0.9 was used for the asphalt used to cover the roof.

In the analysis presented here, a constant inside thermal environment (i.e. the space temperature is taken as 27°C) with period variations of outdoor air temperature and solar radiation intensity is assumed to be prevailing. The diurnal variation of the sol-air temperature T_{SA} is analysed along the lines used by Algifri *et al.*, (1992) as:

$$T_{SA} = T_o + \sum_{n=1}^{\infty} M_n \cos\omega_n\theta + N_n \sin\omega_n\theta \qquad (3)$$

where

$$T_o = (1/24)\int_0^{24} T_{SA}\,d\theta$$

$$M_n = (1/12)\int_0^{24} T_{SA}\cos\omega_n\,d\theta$$

$$M_n \approx (1/12)\int_0^{24} T_{SA}\sin\omega_n\,d\theta$$

$$\omega = 2\pi n/\theta$$

In terms of phase angle this can be written as:

$$T_{SA} = T_o + \sum_{n=1}^{\infty} C_n\cos(\omega_n\theta - \phi_n) \qquad (4)$$

$$C_n = \sqrt{M_n^2 + N_n^2}$$

$$\tan\phi_n = N_n / M_n$$

The resulting temperature of the inside wall surface is determined as:

$$T = T_{in} + (1/h_{si})\left[U(T_o - T_{in}) + \sum_{n=1}^{\infty} V_n C_n \cos(\omega_n\theta - \phi_n - \Phi_n\right] \qquad (5)$$

where

$$V_n = \frac{h_{si}h_{so}}{\sigma_n k\sqrt{Y_n^2 + Z_n^2}}$$

$$\sigma_n = \sqrt{\omega_n/2\delta}$$

$$Y_n = A_1\cos\sigma_n L\sinh\sigma_n L + A_2\cos\sigma_n L\sinh\sigma_n L$$
$$= + A_3\cos\sigma_n L\cosh\sigma_n L$$

$$Z_n = A_1\sin\sigma_n L\cosh\sigma_n L - A_2\cos\sigma_n L\sinh\sigma_n L$$
$$= + A_3\sin\sigma_n L\sinh\sigma_n L$$

$$\tan\Phi_n = Z_n/Y_n$$

$$A_1 = \frac{h_{si}h_{so}}{2\sigma_n^2 k^2} + 1$$

$$A_2 = \frac{h_{si} h_{so}}{2\sigma_n^2 k^2} - 1$$

$$A_3 = \frac{h_{si} + h_{so}}{\sigma_n k}$$

The value of the thermal conductivities, u-values, h_{so} and h_{si} used in this work are those given by Sodha *et al.* (1986) and Markus and Morris (1980). The solar radiation incident on the walls and roof for the four directions have been estimated from the CPCR2 result using the Lui and Jordan method as given by Duffie and Beckman (1991). The Fourier coefficients were determined and only six coefficients were used since this number is generally sufficient to describe the periodic variation.

RESULTS

The results for the 15th of October 1996 and 3rd January, 1997 have been obtained for the purpose of this study. The first six harmonics for the Fourier series of the sol-air temperatures for the two chosen days are shown in Tables 2a and 2b for the different surfaces.

Table 2a: *Fourier coefficients for the daily variation of sol-air temperature on horizontal and various surfaces for 15th October, 1996. (AMP and f are amplitude and phase of Fourier coefficient respectively)*

	n	0	1	2	3	4	5	6
Horizontal	AMP (°C)	36.70	35.776	15.043	5.459	0.479	1.013	0.208
	ϕ(rad)	-	0.000	0.661	0.941	0.822	1.292	0.946
NE Wall	AMP (°C)	29.43	28.899	10.422	3.965	0.764	0.646	0.206
	ϕ(rad)	-	0.000	0.887	1.399	0.181	1.329	1.214
SE Wall	AMP (°C)	28.07	27.499	8.266	2.147	1.541	0.803	0.277
	ϕ(rad)	-	0.000	0.737	0.481	0.935	1.043	0.288
NW Wall	AMP (°C)	27.12	26.671	8.423	2.417	0.751	0.862	0.183
	ϕ(rad)	-	0.000	0.930	1.396	1.143	1.362	0.454
SW Wall	AMP (°C)	26.70	26.166	7.638	1.704	0.852	0.310	0.546
	ϕ(rad)	-	0.000	0.004	1.028	1.178	1.180	0.586

The result for 15th October represents a day of high outside air temperature and high incident solar radiation. The sol-air temperature was obtained as described and the inner surface temperatures of the building were obtained and are shown in Fig. 2 for 15th October 1996. The temperatures of the inner surfaces of the building apart from the inner roof temperatures are higher than the ambient between 4:00 hours and 10:00 hours and subsequently go lower than the ambient till 21:00 hours when they again exceed it. The South-East wall's temperature shows lower temperatures than those of the other walls at the afternoon period. Maximum temperature differences at the afternoon period is about 17°C for the South-East wall while those of the other surface are not very far from this. The temperature swing for this period for the inner wall surfaces was between 8.5 and 11.1°C. The importance of this is that the building material is able to keep the building at a lower temperature than the outside air temperature when the latter is high. The ceiling temperature of the roof shows a consistently lower temperature than the outside air temperature and equals the outside air temperature just briefly between 17:00 and 18:00 and becomes higher at 22:00 and 23:00 hours.

The results for a cold day is shown in Fig. 3 for the 3rd of January 1997. The thermal responses show clearly that the bricks respond well thermally by keeping the inner surfaces warmer than the outside air temperature. Between 12:00 and 20:00 hours the temperatures are lower than the outside air temperatures which are high at these hours. The temperatures are higher than those of October. The temperature swing for the inner roof in this period is only 5.0°C.

The results clearly show that the mud bricks can serve well in terms of the thermal comfort of these types of buildings. Table 3 shows a summary of the thermal analysis for temperatures for the inner surfaces of the different directions and the lag times for the achievement of these temperatures and finally the temperature swings for the different seasons considered.

CONCLUSION

The analysis presented show the appropriateness of the NBRRI bricks for the construction off dwelling houses for the hot climate of Kano. There are many implications of this result one of which is that there is the possibility of a major savings of energy consumption which would otherwise have been needed for cooling. Again the fact that laterite is in abundance all over the place makes these bricks attractive to use and of course the production uses

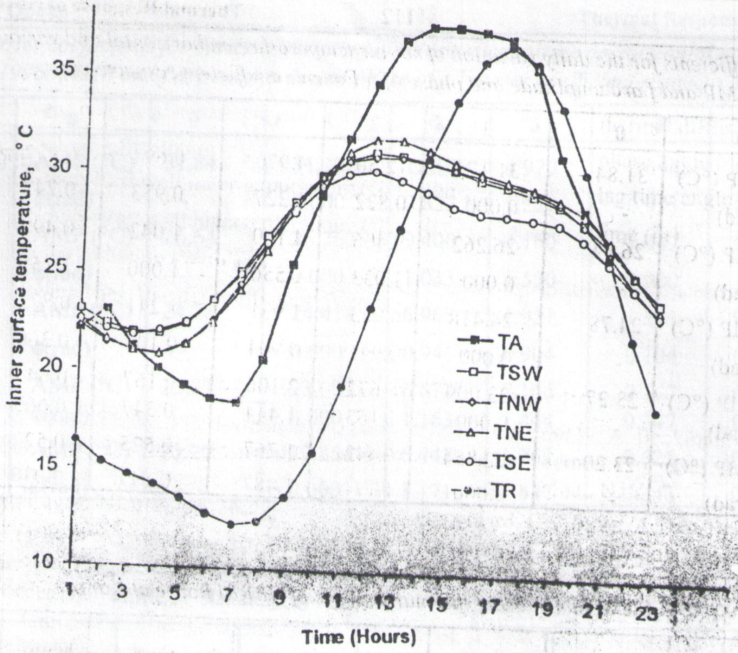

Figure 2: Computed inner surface temperatures of NBRRI mdel house in Kano compared with the ambient temperature for 15th October, 1996.

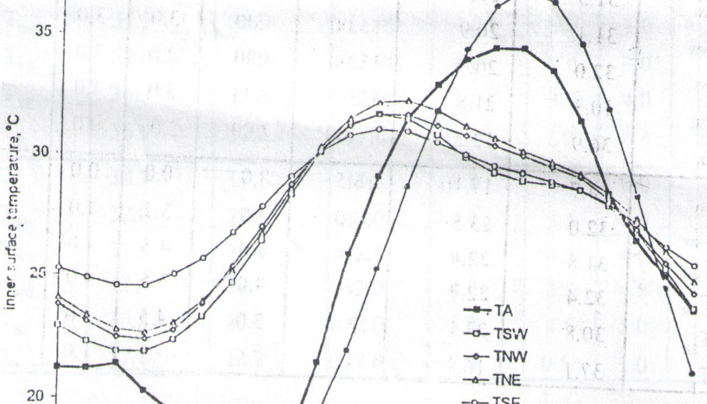

Figure 3: Computed inner surface temperatures compared with the ambient temperature for NBRRI model house situated in Kano, Nigeria for 3rd January, 1997.

Table 2b: *Fourier coefficients for the daily variation of sol-air temperature on horizontal and various surfaces for 3^{rd} January, 1996. (AMP and f are amplitude and phase of a Fourier coefficient respectively)*

	n	0	1	2	3	4	5	6
Horizontal	AMP (°C)	31.84	31.175	12.509	4.970	0.694	0.952	0.227
	φ(rad)	-	0.000	0.822	1.227	0.953	0.747	0.144
NE Wall	AMP (°C)	26.64	26.262	9.406	4.160	1.042	0.499	0.434
	φ(rad)	-	0.000	1.033	1.550	1.000	1.155	0.259
SE Wall	AMP (°C)	24.78	24.418	6.963	1.931	1.241	0.872	0.088
	φ(rad)	-	0.000	0.941	0.904	0.104	0.360	0.466
NW Wall	AMP (°C)	23.27	23.009	6.672	2.106	0.167	0.643	0.347
	φ(rad)	-	0.000	1.163	1.444	0.347	0.663	0.408
SW Wall	AMP (°C)	23.20	22.854	6.442	1.767	0.525	0.522	0.244
	φ(rad)	-	0.000	1.171	1.487	0.143	0.030	1.081

Table 3: *Summary of thermal analysis of NBRRI house at Kano.*

Day	Surface	Max. Temp.°C	Min. Temp.°C	Time Achieved, (Hours)		Lag time, (Hours)		Temp. Swing $T_{max}-T_{min}$
				Max Temp.	Min. Temp.	Max. Temp.	Min. Temp.	
October 15th 1996	T_A	37.8	18.5	15:00	7:00	0.0	0.0	19.3
	T_{SW}	31.3	21.9	12:00	4:00	3.0	3.0	9.4
	T_{NW}	31.1	20.9	12:00	4:00	3.0	3.0	10.3
	T_{NE}	32.0	20.9	13:00	4:00	2.0	3.0	11.1
	T_{SE}	30.3	21.8	12:00	3:00	3.0	4.0	8.5
	T_R	36.9	12.2	17:00	7:00	-2.0	0.0	24.7
January 3rd 1997	T_A	34.7	17.10	16.5	8.0	0.0	0.0	17.6
	T_{SW}	32.0	23.5	13.0	4.0	3.5	4.0	8.4
	T_{NW}	31.8	22.4	12.0	4.0	4.5	4.0	9.4
	T_{NE}	32.4	22.7	13.0	4.0	3.5	4.0	9.4
	T_{SE}	30.8	23.1	12.0	3.0	4.5	5.0	7.7
	T_R	37.1	16.1	17.0	7.0	-0.5	1.0	21.0

every little energy and does not contribute very much to environmental pollution as compared to the process of production of other building materials such as cement. The only problems are those of attendant erosion due to over exploitation which rain which can be tackled through better materials engineering methods.

Future work will focus on experimental validation of the above results and also investigate some passive methods to improve upon the thermal response of such buildings.

NOMENCLATURE

h_r = radioactive heat transfer coefficient (W/m²K)
h_{si} = inside wall heat transfer coefficient (W/m²K)
h_{so} – outside wall heat transfer coefficient (W/m²K)
k – thermal conductivity of wall material (W/m²K)
L = thickness of wall material (m)
n = order of harmonics in Fourier series
T_A – outside air temperature (°C)
T_{in} = inside environment space temperature (°C)

T_{NE} = North-East wall inner temperature (°C)
T_{NW} – North-West wall inner temperature (°C)
T_R = roof inner surface temperature (°C)
T_{SA} = Sol-air temperature (°C)
T_{SE} = South-East wall inner temperature (°C)
T_{SW} = South-West wall inner temperature (°C)
S = solar radiation (W/m^2)
U = overall heat transfer coefficient (W/m^2K)

Greek symbols

α = absorptivity of the surface
δ – thermal diffusivity (m^2/hr)
ϕn = phase angle (deg)
Φn = lag time angle (deg)
θ = time (hr)

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