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Comparison of the thermal properties of clay samples as potential walling material for naturally cooled building design

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Abstract: The thermal properties of different clay samples obtained from locations in Akwa Ibom State, Nigeria were investigated and compared, and in order to establish their suitability as building material from energy conservation point of view. The results showed that stoneware clay has the highest solar radiation absorptivity of 22.32 m^{-1} while kaolin clay has the lowest radiation absoptivity of 14.46 m^{-1}. A model for the prediction of temperature variation with thickness of the samples was developed. Results showed that kaolin would make the best choice for the design of a naturally cooled building.

Keywords: thermal properties; clay; walling material; naturally cooled building

Introduction

Heat which is transmitted through walls, either during the day or retained by the walls and transmitted at night by the processes of conduction and radiation is one of the factors causing discomfort in interior spaces in the tropical region. The effect of this heat could be minimized or totally eliminated if the walling material is made up of proper thermal insulating material. Many materials used for wall construction, like glass, zinc etc. are conductors of heat. Various attempts are presently being made to source for local materials with suitable structural and energy-conserving properties(Ajibola, 1994).

At present, cement that can be used for building purposes is very expensive and has gone beyond the reach of the low income earners. This calls for alternative sources of building materials. Examination of some alternative sources of soil-based materials established that there are many soil resources, which are suitable for construction. Ekpe and Akpabio (Ekpe, 1994) examined thermal properties of some soil samples and established that laterite is a suitable material for passively cooled building design.

Another type of soil is the clay soil. There are many types of clay ranging from pure kaolins to shales. The thermal properties of these clay samples are, however, not well established, but the mineralogical analysis of the clay samples had been done. Studies have shown that the particle size of clay is very important characteristic, since it influences many other properties such as plasticity, dry strength, and base exchange capacity. However, very little has been known about the exact shape of clay particles (Norton, 1974). Particles size for clay soils ranges from 0.002 mm and below(Ekpe, 1994).

Variations in temperature with thickness of the soil determines whether the soil can be used as heat source or sink. Heat flow through any soil sample depends on the thermal properties of the soil(Ekpe, 1994; Akpabio, 1999; Moustafa, 1981).

The purpose of this study is to develop a model for the prediction of temperature variations with thickness of the clay samples which could be used as a guide for the choice of the type of clay for a naturally cooled building design.

1 Theory

A number of factors, which include site, geographic characteristic and thermal physical properties determine soil temperature(Mahrer, 1982). The amount of radiant energy that reaches the soil surface, color of the soil, and thermal properties of the soil determine variations in temperature with thickness. The color determines the proportion of the radiant energy absorbed or reflected by the soil. The changes in temperature of the soil is caused by the proportion of the energy absorbed. This energy absorbed by the surface may be used in heating the air outside the soil, increasing surface temperature, heating the interior layers of the soil or radiating to the atmosphere(Mahrer, 1982; Ekpe, 1994; Akpabio, 1999). The heat budget equation can be expressed thus: Heat flow through the material = Heat absorbed from atmosphere + absorbed solar radiation-Re-emitted radiant energy. The above energy balance equation, in one dimension, can be expressed as:

$$-K(\partial T/\partial x)_{x=0} = h(T_{\mathrm{atm}} - T_{x=0} + \alpha I - \in \Delta R, \tag{1}$$

where K is the thermal conductivity of the soil; T is the soil temperature; h is the heat transfer coefficient at the surface; T_{atm} is the atmospheric air temperature; α is the solar radiation absorbtivity at the surface; I is the intensity of solar radiation; $\in$ is the long-wave emissivity of the surface; ΔR is the difference between the incident long wave radiation and the radiation emitted from the surface.

Solar temperature T_s is given as

$$T_s = T_{\mathrm{atm}} + (\alpha I/h) - (\in \Delta R/h). \tag{2}$$

Based on the above, a general solution of the form:

$$T(x,t) = a_0 + \sum_{M=1}^{\infty} \{a_m \exp[i(m\omega t + \alpha_m x]]\} \tag{3}$$

is assumed (Moustafa, 1981). Where $\alpha_m = (m\omega\rho c/2k)^{1/2}(1-i)$; C is the specific heat capacity of the soil; ρ is the density of the soil; and $\omega = 2\pi/(\text{period } T)$. Eq.(3) shows the dependence of soil temperature with thickness on the periodic variation of temperature at the surface(Ekpe, 1994). From Eq.(3), we have:

$$T(x,t) = a_0 + \sum_{M=1}^{\infty} \{a_m \exp(-\alpha_m x)\cos(m\omega t - \alpha_m x)\}. \tag{4}$$

Modifying Eq.(4) into a convenient form, we have:

$$T(x,t) = T_m - A_s \exp(-\alpha x)\cos[\omega(t - t_0) - \alpha x/\omega]. \tag{5}$$

Where A_s is the daily temperature amplitude at $x = 0$, ℃; t is the time of the day in hour, t_0 is the time of minimum temperature at the surface. T_m can be calculated from the hourly soil surface temperature average Thss, T_{hss}, ℃ as

$$T_m = \sum_{M=1}^{24} (T_{\mathrm{hss}}/24). \tag{6}$$

On a 24 hour period, Eq.(5) takes the form:

$$T(x,t) = T_m - A_s \exp(-\alpha x)\cos[(2\pi/24)(t - t_0) - 12\alpha x/\pi]. \tag{7}$$

2 Material and method

Six different types of clay samples, namely; terra-cotta, kaolin, kaolinatic clay, stoneware or black clay, ball and earthenware clay were collected from Idim Afia in Eket, Mkpat Enin, Oruk Anam, Ukpom Edem Inyan in Oruk Anam, Itam in Itu and Ikot Akpan Udo in Ikot Abasi respectively. All the clay samples studied were prepared by drying at a temperature not greater than 45℃ to constant mass, were ground to powdery from and some deionized water added to each of the samples for mixing and molding into required shape. The molded samples were again subjected to slow drying at a temperature not greater than 45℃ to constant mass and was reshaped to the required diameter and thickness. The prepared samples were finally stored in a desicator at room temperature, ready for thermal properties determination.

Thermal conductivities were determined for each of the clay samples using the steady state method. Lee's disc apparatus was modified and adapted for use. Dry samples were used to avoid the problem of redistribution of water under the influence of a temperature gradient(Eke, 1994; Tyler, 1971). Akpabio and Eke(Akpabio, 1998) assumed that under steady condition, the heat conducted across the soil sample is equal to the rate which it is emitted from the exposed surface. Specific heat capacity for each sample was determined by method of cooling correction(Nelkon, 1982; Tyler, 1971). Weighing and displacement method was used for the determination of bulk density (Nelkon, 1982). Thermal diffusivity ($\lambda = k/\rho c$) and absorptivity, $\alpha = (\omega/2\lambda)^{1/2}$ were also calculated for each clay sample.

3 Results and discussion

Table 1 shows the results for the thermal conductivity, K; specific heat capacity, c; bulk density, ρ; diffusivity, λ; and absorptivity, α; for the six clay samples. From Table 1, it is noted that stoneware clay has the highest solar radiation absorptivity of 22.32 m^{-1}, followed by terra-cotta with 19.36 m^{-1}, ball clay, earthenware clay and kaolinatic clay has solar radiation absorptivity of 17.06 m^{-1}, 15.89 m^{-1} and 15.10 m^{-1} respectively, while kaolin has the least solar radiation absorptivity of 14.46 m^{-1}.

Table 1 Thermal properties of clay samples

S/n	Clay samples	Thermal conductivity K, W/(m·K)	Specific heat capacity C,(J/(kg·K) × 10^3	Bulk density ρ,(kg/m^3) × 10^3	Diffusivity λ,(m^2/s) × 10^{-7}	Absorptivity α,m^{-1}
1	Terra-cotta	0.383	2.19	1.29	0.97	19.362
2	Kaolinatic	0.434	1.70	1.60	1.59	15.099
3	Stoneware	0.388	2.94	1.80	0.73	22.319
4	Ball	0.383	1.68	1.81	1.25	17.056
5	Kaolin	0.370	1.19	1.78	1.74	14.457
6	Earthenware	0.463	1.64	1.96	1.44	15.891

Substituting the respective values of the solar radiation absorptivity, into Eq. (7) we have the following equations for predicting the sample temperature at any given thickness, x and time of day, t for each clay sample used.

For terra-cotta:

$$T_{(x,t)} = T_m - A_s \exp(-19.36x)\cos[0.262(t - t_0) - 73.95x]. \tag{8}$$

For kaolinatic clay:

$$T_{(x,t)} = T_m - A_s \exp(-15.10x)\cos[0.262(t - t_0) - 57.67x]. \tag{9}$$

For soneware clay:

$$T_{(x,t)} = T_m - A_s \exp(-22.32x)\cos[0.262(t - t_0) - 85.24x]. \tag{10}$$

For ball clay:

$$T_{(x,t)} = T_m - A_s \exp(-17.06x)\cos[0.262(t - t_0) - 65.14x]. \tag{11}$$

For kaolin:

$$T_{(x,t)} = T_m - A_s \exp(-14.46x)\cos[0.262(t - t_0) - 55.21x]. \tag{12}$$

For earthenware clay:

$$T_{(x,t)} = T_m - A_s \exp(-15.89x)\cos[0.262(t - t_0) - 60.69x]. \qquad (12)$$

Eqs.(8), (9), (10), (11), (12) and (13) are the required model for predicting temperature variation with thickness of the clay samples used.

The values of the thermal conductivity obtained from the experiment are compared with the values of thermal conductivity of other commonly used building materials. As shown in Table 2, the six clay samples have thermal conductivity lower than all non wood-base building materials, with kaolin having the lowest. This means it offers more resistance to the passage of heat through it than other clay materials and other building materials like Brick, R.C.C (1.2.4) cement plaster and glasses.

Table 2 Comparison of some thermal properties of clay materials with other commonly used building material

Building materials	Density, kg/m^3	Thermal conductivity, Wm^{-1}K^{-1}	Thermal resistivity, W^{-1}mK
Brick	1820	0.697	1.43
R.C.C. (1.2.4)	2288	1.360	0.735
Cement plaster	1762	0.620	1.61
Glass	2350	0.701	1.42
Earthenware clay	1960	0.463	2.16
Kaolinatic clay	1600	0.432	2.30
Stoneware clay	1800	0.388	2.58
Terra-cotta	2190	0.383	2.61
Ball clay	1810	0.383	2.61
Kaolin	1190	0.370	2.70
Softwood	480	0.062	16.13
Hardwood	720	0.124	8.06
Plywood	530	0.140	7.14
Woodchip board	800	0.150	6.66
Coconut trunk	720	0.115	8.69

Source: Ajibola, K. and Onabonjo, B. O. 1994 and calculations from experimental data

4 Conclusions

From our experimental results, kaolin has the least solar radiation absorptivity as well as the least thermal conductivity, hence high thermal resistivity. From the models developed for the prediction of temperature variation with thickness of the samples kaolin would, during the hottest time of the day (13 hours Nigerian time), record a lower temperature than other clay samples used. It is, therefore, concluded that kaolin would make a better choice over other clay materials in the design of a naturally cooled building.

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