MODELLING OF THE THERMAL CONDUCTIVITY PROPERTY OF A NEWLY DEVELOPED THERMO-REGULATED BRICK

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ABSTRACT

The work modelling of the thermal conductivity property of a newly developed thermo regulated brick has been extensively carried out. The brick was developed from anthill clay and cement and the various properties of the bricks were investigated, however, for this particular work the property of interest was the thermal conductivity. The thermal conductivity data was used for developing a prediction model using linear adaptive filter. This model was used with variables from the previous work and the model produced results similar to the desired output. A plot of the prediction values and the actual thermal conductivity values on the same graph showed the two curves lying in the same position (tight-fit) clearly indicating the accuracy of the prediction model. This was also confirmed by the performance evaluation of the developed model. The mean square error was 1.2441E-023 which indicated negligible variation from the actual thermal conductivity values.

Keywords: Thermal conductivity; Newly developed; Brick; Thermoregulation; Modeling.

INTRODUCTION

A new thermo-regulated brick has been developed using anthill clay and cement additive. Anthill structure has been known to have thermoregulation property. The structure has the ability to regulate its own internal temperature. No matter the external temperature; the temperature within the anthill structure hardly exceeds 27^{o}C. This secret was long realised by the rural dwellers of Northern Nigeria. For so many centuries they have been using this anthill clay for building of their huts and barns for storage of their food crops and grains. Because of the thermoregulation properties of the barns they were able to preserve these food crops till the following season [1].

Of recent some sections of the Northern part of Nigeria have been able to produce fired bricks using this anthill clay in order to improve on the resistance to water wettability by the clay. Water reduces the strength of buildings built using anthill clay and for such buildings to last the water absorption ability of the clay must be reduced [1]. This was accomplished in this present work also by the addition of controlled amount of cement to anthill clay, instead of firing the bricks. This was however, done at a cost and the cost was the slight change in the thermal conductivity of the anthill clay which is very important in its thermoregulation property. According, to Chesti [2] low thermal conductivity provides high insulation and prevents heat losses. Anthill clay minimises the heat from the environment that will enter the structure and at the same time conserves the absorbed heat thereby maintaining a constant temperature within. The present global warming with its attendant effects call for the use of these thermo-regulated bricks in order to mitigate extreme temperatures, and building collapse due to flooding incidences [3-5].

In the development of the thermo regulated bricks thermal conductivity is one of the important parameters particularly as it concerns the thermo regulation property of the clay.

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Studies have shown a strong correlation between this property and thermal conductivity as the thermal conductivity increases this property is gradually lost [1,6-7]. And that is what informed the decision for the anthill clay thermal conductivity to be the benchmark upon which a model can be developed so that the thermal conductivity of a brick can be predicted and compared with the benchmark for thermo regulated bricks. In this work the prediction model used is called adaptive linear neural network filter.

This is a form of neural network with linear activation function that is controlled by variable parameters or weights which are adjusted according to an optimization or a learning algorithm. Adaptive filters are required for some applications because some parameters of the desired process are not known in advance or are changing in a stochastic manner. The closed loop adaptive filter uses feedback in form of an error signal to refine its activation function. Furthermore, the closed loop adaptive process involves the use of a cost function or an objective function, which is a criterion for evaluating the optimum performance of the filter. A learning or optimisation algorithm which determines how to modify the filter transfer function in order to minimize the cost function on the next iteration is adopted. The most common cost function is the mean square of the error signal [8].

The idea behind a closed loop adaptive filter is that a variable filter is adjusted until the error (the difference between the filter output and the desired signal) is minimized. The Least Mean Squares (LMS) filter and the Recursive Least Squares (RLS) filter are types of adaptive filter. Fig. 1 presents the Compact representation of a closed loop linear adaptive filter. k represents the sample number; x is the reference input; d is the desired input; ε is the error output; f is filter impulse response; Σ is the summation; and the box represents the linear filter and adaption algorithm. In this research, the LMS algorithm was adopted. The LMS algorithm or Widrow-Hoff learning algorithm is based on an approximate steepest descent procedure [9-10].

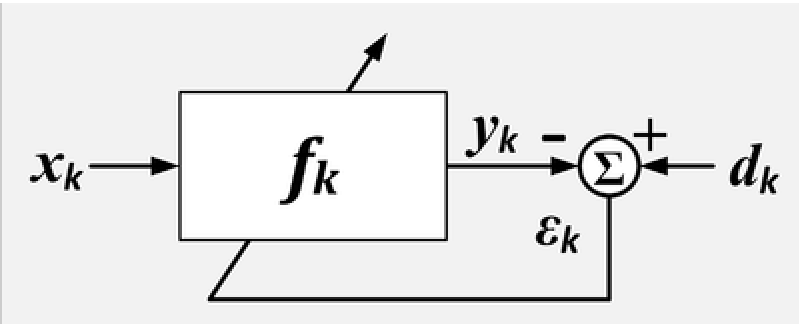

Fig. 1: Compact representation of Adaptive Filter

The objective of this work is to provide a model that will help in the prediction and regulation of the thermal conductivity of the developed brick, so that it will not be too different from the thermal conductivity of the anthill clay. This is necessary for the attainment of thermoregulation when the bricks are used in the building of houses and barns for food preservation.

MATERIALS AND METHOD

Materials and Equipment

The materials for this study were Anthill Clay (primary), Cement (secondary) and distilled water. Samples of the primary material were collected from different locations in the selected study area, Uyo and Port Harcourt, while the additive sample was obtained from the concrete

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laboratory in the University of Uyo, Akwa Ibom State. The grade of additive used in the experiment was Cement grade 42.5 with high alumina content for general purpose engineering applications. Other materials were: distilled water, releasing agent (engine oil), filter papers, cellotape, writing materials, chemical reagents, cleaning cloth and fumigation chemicals (DDT).

Equipment

Equipment used were as follows: Atomic absorption spectroscope, Ignition burner, Analytical weighing balance (0.1g sensitivity) and weight box, Multi-purpose digital pH meter, Reciprocating shaker, Dispensing bottles, pipettes, beakers, Erlenmeyer and volumetric flasks (125ml), Thermometer (Hand thermo flash, max. 40^0C and Digital Sensor, 200^0C), Water distillation unit and evaporation dishes (aluminium), Drying oven (controlled at 105 -110^0C) and hot plate (150^0C). Others were Refrigerator and desiccators, I.S set of sieves, metal cans (lid), glass plate, measuring cylinder, oven, measuring pan, limit device, grooving tools and spatula, cylindrical steel mould, rammer, trowel, mixing pan, water cans, steel straight edge, steel ruler, Brick mould 215 x 102.5 x 65mm [16], Detachable steel moulds of 100 x 100 x 100mm, Computerized universal testing machine (DIGIMAX 3 Control, capacity of 3000KN), and Electrical furnace (max. 1200^0C).

Method

With the materials and equipment listed above thermoregulatory bricks were produced. Both the raw materials and the produced bricks were subjected to various tests ranging from chemical analysis to physical and mechanical tests. The control brick upon which the development revolved had no cement additive. The brick however had the property of interest which was thermo regulation. For the purpose of this work the details of the previous research work cannot be reproduced, it can however, be found in reference [1]. The conductivity data of the developed bricks shown in Table 1 was generated from this work which was carried out at University of Uyo-Nigeria. The experimental procedure used in generating the data is briefly described below:

Thermal Conductivity

The thermal conductivity measurement test was conducted according to an adapted experimental procedure of international standards [8](ASTM Standard, 2000). The specific steady state technique used in this research is known as the “Guarded Hot Plate Method”. The scheme of guarded hot plate is shown in Figure 2.1.

The brick specimens were placed between two plates. One plate (hot plate) was heated to a temperature of 150^0C and the other plate (cold plate) was immersed in water to a temperature lower than the hot plate. The cold plate was of equal cross section with the brick specimens while the hot plate was of smaller cross sectional area. This was ensured to avoid heat transfer via radiation from the hot plate to the cold plate. Also insulation was effected by forming the set up in ceramic sink. The sink was covered with a ceramic tile for complete insulation. The temperature of the plates was monitored until they had a constant value. The steady state temperatures, the thickness of the sample and the heat input to the hot plate were used to determine thermal conductivity.

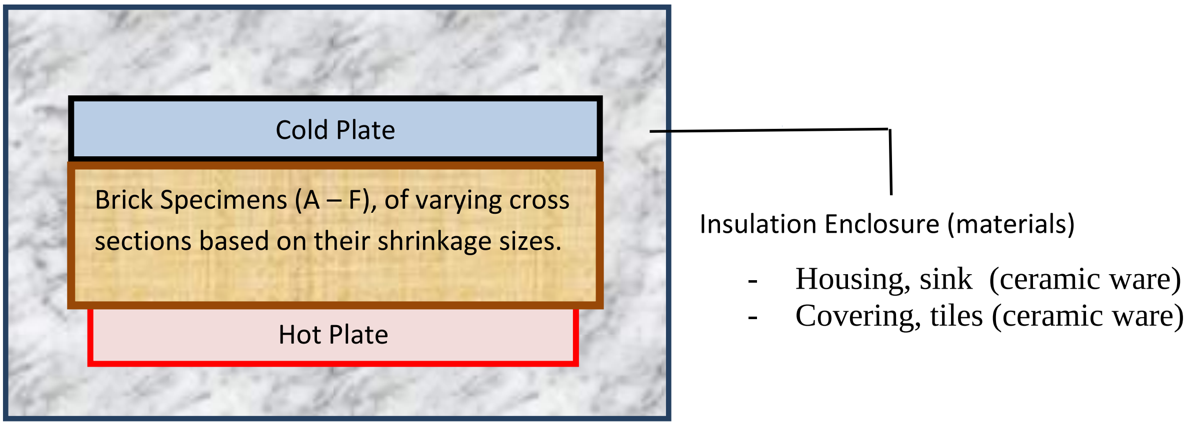

Fig. 2. Schematic Representation of the Guarded Hot Plate Method Set up Utilized for Thermal Conductivity Test.

Table 1 Thermal Conductivity data of Anthill Clay + Cement (0-20% additives)

Brick Specimen, PA	Q(W)	D(m)	ΔT(K)	$q(W/m^2)$	Thermal Conductivity, λ (W/m^2)
Anthill Clay +Additive (0%)	0.4350	0.0630	2.1000	20.7140	0.6210
Anthill Clay +Additive (5%)	0.4490	0.0630	1.8000	17.2700	0.6200
Anthill Clay +Additive (10%)	0.5670	0.0600	2.5000	26.2500	0.6300
Anthill Clay +Additive (15%)	0.6840	0.0650	3.0000	31.2330	0.6770
Anthill Clay+Additive (20%)	0.6980	0.0650	2.9000	31.7270	0.7110

RESULTS AND DISCUSSION

Development of the prediction model using Linear Adaptive Filters

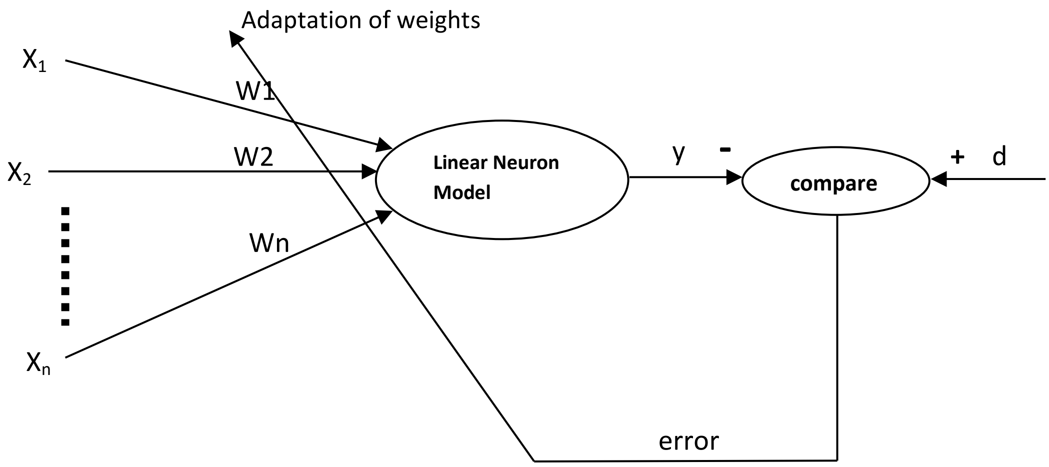

Fig. 3 Adaptive Linear Neuron Model

The predicted output vector from the neuron $\mathbf{y} = \mathbf{X}\,\mathbf{w}$……………………………... (1)

Where, **X** is an n-by-m data matrix; n is the number of training examples and m is the number of features. **w** is an m-by-1 weight vector.

Cost function for the prediction

Assuming an iterative batch learning, the error vector for the jth epoch becomes

e(j) = **d**(j) – **y**(j) ………………………………………………………………… (2)

Where, **d** is the desired output vector.

The Mean square Error (MSE) = $\frac{\sum_{j=1}^{n} e^2(j)}{n}$ ………………………………… (3)

Substituting equation (1) into (2)

e(j) = **d**(j) – **X**(j)**w**(j) ………………………………………………………………(4)

To minimise the error function, we differentiate equation (1); thus:

$\nabla \mathbf{e}(j) = -\mathbf{X}^T(j)$

where, $\mathbf{X}^T$ means the transpose of matrix **X**

But, $\nabla \mathbf{e}(j) = \mathbf{J}(j) = \begin{pmatrix} \frac{\partial e(1)}{\partial w1} & \cdots & \frac{\partial e(1)}{\partial wm} \\ \vdots & \ddots & \vdots \\ \frac{\partial e(n)}{\partial w1} & \cdots & \frac{\partial e(n)}{\partial wm} \end{pmatrix} = -\mathbf{X}^T(j)$ ……………………………………(5)

n-by-m matrix

Where, **J** (j) is the Jacobian matrix.

From Gauss-Newton optimisation algorithm

$\mathbf{w}(j+1) = \mathbf{w}(j) - (\mathbf{J}^T(j)\mathbf{J}(j))^{-1}\mathbf{J}^T(j)\mathbf{e}(j)$ …………………………………………………...(6)

where, $\mathbf{J}^T(j)\mathbf{J}(j)$ is assumed to be non-singular and thus its inverse exists.

Substituting equations (4) and (5) into (6)

$\mathbf{w}(j+1) = \mathbf{w}(j)+(\mathbf{X}^T(j)\mathbf{X}(j))^{-1}\, \mathbf{X}^T(j)\, (\mathbf{d}(j)-\mathbf{X}(j)\mathbf{w}(j)) = \mathbf{w}(j)+(\mathbf{X}^T(j)\mathbf{X}(j))^{-1}\, \mathbf{X}^T(j)\mathbf{d}(j)-\, (\mathbf{X}^T(j)\mathbf{X}(j))^{-1}\, \mathbf{X}^T(j)\mathbf{X}(j)\mathbf{w}(j))$

$\mathbf{w}(j+1) = (\mathbf{X}^T(j)\mathbf{X}(j))^{-1}\, \mathbf{X}^T(j)\mathbf{d}(j)$ ……………………………………………………….(7)

Using the data available in Table 1, a MatLab program (appendix A_) developed to accurately give the weight vector **w** using the normal equation (7) such that **y** ≈ **d** .

The prediction models and graphs showing how close the **y** is to **d** for Table 1 are provided below:

For Table 1*:*

Prediction model: λ = -0.0031(PA) + 0.4206Q + 9.2353D - 0.3129ΔT+ 0.0248q ....(8)

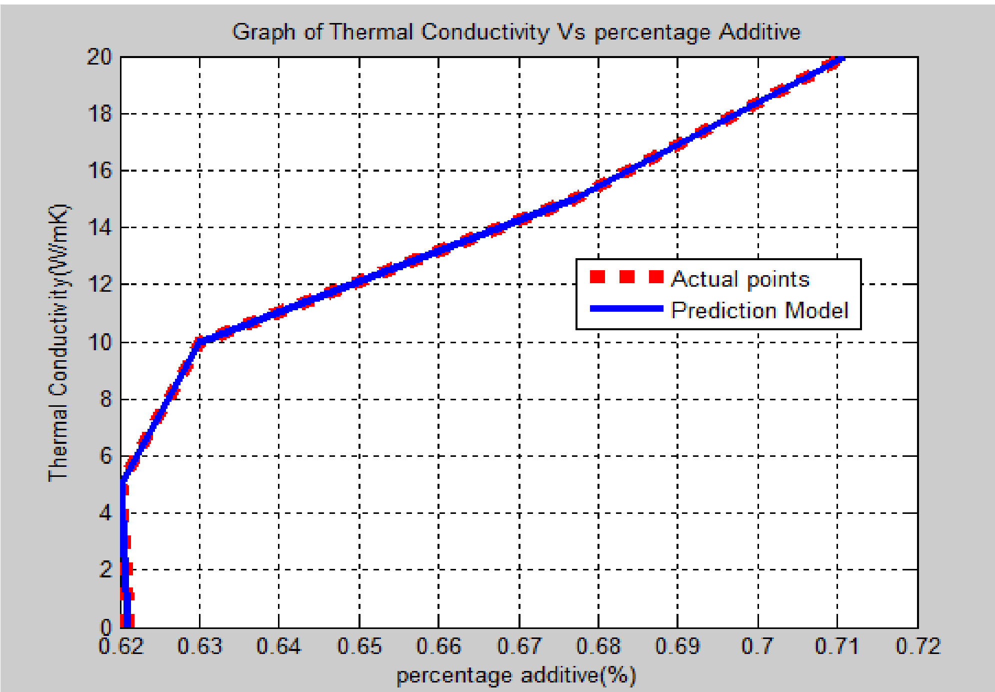

Fig 4: Comparison between the prediction model and actual output for Table 1

Performance Evaluation of the Prediction Models
The prediction models are evaluated using equation (3)

$$\text{MSE} = \frac{\sum_{j=1}^{n} e^2(j)}{n}$$

But, **e**(j) = **d**(j) – **X**(j)**w**(j) from equation (4)

For Table 1:

MSE = 1.2441E- 023 .... (9)

See appendix A for MatLab Code used

DISCUSSION
Thermal Conductivity

able 1 shows the experimental values of thermal conductivity and other parameters of the various bricks. The data in the table was used to develop a prediction model as shown in equation 8. Input variables from Table 1 were imputed into equation 8 to generate various values of **y** (The predicted output vector from the neuron) and these values were compared with d (the desired output) in Table 1. The comparison is shown in fig. 4 where the plot of **y** and **d** is made on the same graph. The accuracy of the prediction model can clearly be seen in the graph, the curve of **y** and **d** are lying on each other indicating how close the prediction model is to the desired output **d**. The illustration in the graph is confirmed by the mean square error equation 9 which indicates that the error is actually very small, negligible and insignificant.

According to Ihom, [12] prediction model can be used in producing thermo-regulated bricks with the desired output and in this case, thermal conductivity which is a very important property of thermo-regulated bricks can be predicted using the developed model. Table 1 shows that thermal conductivity is directly proportional to cement content in the anthill clay bricks, as the cement content of the bricks is increasing so also is the thermal conductivity increasing, showing a steady rise of the curve in fig.4. The highest thermal conductivity value of 0.71 W/mK occurred at 20% cement while the lowest value of 0.62 W/mK, thermal conductivity occurred at 0% cement content in the brick.

The results are within the acceptable standard values of 0.6 – 0.8W/mK for structural clay bricks (ASTM C177-97 Standards, 2000) in [1]. However, 10% cement content brick will be preferred because of its optimum properties and closeness to 0.62 W/mK value of the 0% cement brick. This is an added advantage to fully utilize the thermoregulation properties of the anthill clay. Mekine [1] in his work observed that density does not control thermal conductivity but it is the cement added to the anthill clay that does. He further observed that thermal conductivity increases while density gets to its highest peak of 1878 kg/m^3 at 10% cement and then starts decreasing down to 1836kg/m^3 at 20% cement brick. Theories on the relationship between thermal conductivity of clay bricks and density of the bricks, say the denser the brick the higher the thermal conductivity and the porous the brick the lower the thermal conductivity of the bricks [2]. The result therefore agrees with the existing theory. Anthill clay (0% cement) being the control specimen has the lowest thermal conduction ability which is a desirable functional requirement with regards to thermoregulation in the aspects of storage (food produce) and shelter (habitation). But total concentration on this natural property, neglecting other engineering properties renders standardization of the Anthill clay material futile. Hence the selection of brick specimens 5 – 10%, considering other parameters is a technical choice [13-15]. Mekine [1] also showed a non-dependence of the thermal property on the maximum dry densities of the samples despite the optimum density value being at 10% additive as explained above. This is also partly due to physical properties of the anthill clay (mild –plastic) and that of the cement (hydraulic material) which introduces conducting elements in the mix (electrolytes) according to Bogue [13]. From the results of Mekine's work the plasticity of the Anthill clay tends to reduce the heat flow rate in the admixture, while the hydraulic nature (chemically reactive) due to the composition of Tricalcium Silicate ($3CaO:SiO_2$, C_3S) aids the flow rate resulting in the increase in thermal conductivity values indicated in Table 1[1,16]. The above no doubt underscores the complexity of developing a thermo regulated brick and this underpins the need for a prediction model of the type developed in this work.

CONCLUSION

This work the Modelling of the Thermal Conductivity Property of a Newly Developed Thermo-Regulatory Brick has been extensively executed and the following conclusions are drawn from the work:
1. Given the many variables involved in the production of a thermoregulatory brick from anthill the use of linear adaptive filter to develop a prediction model will enhance conformation to thermal conductivity specification of the bricks.
2. The work has developed a prediction model which has accurately produced results which are similar to the desired output
3. The variation (MSE) of the prediction values from the desired output values is actually very small and negligible.
4. The plot of predicted values and actual thermal conductivity values on the same graph confirms the accuracy of the developed prediction model.

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Appendix A: MatLab Code

```
clc; clear; clear all;clf;
%Thermal Conductivity
%X = load(‘dataInput1.csv’);
%y = load(‘dataOutput1.csv’);
X_dagger = pinv(X'*X)*X';
w = X_dagger*y;
T = X*w;
plot(y,X(:,1),'Xr','MarkerSize',10,'Linewidth',2)
hold on
plot(T,X(:,1),'b','LineWidth',3)
legend('Actual points','Prediction Model',0)
grid on
```