Development and Performance Evaluation of Locally Fabricated Thermal Conductivity Apparatus

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ORIGINAL RESEARCH

Abstract- This paper presents the design and construction of a Guarded Hot Plate (GHP) apparatus for the accurate assessment of thermal conductivities of some Nigerian local building materials. The GHP apparatus is a steady-state measurement device. This apparatus is designed to measure the thermal conductivities of masonry building materials of different compositions. The design features included hot and cold plates fabricated with aluminium plates of 6 mm thickness and varying dimensions; the guard plates also made of aluminium, but of 6.35 mm thickness, forms a rigid enclosure for the specimen all encased in a mild steel housing. The operating measuring temperature range is from -20°C to 400°C for varying specimen thickness up to 60mm. Results are presented for concrete, laterite, and a mixture of cement with laterite, clay, and sand respectively, and it covers a range of thermal conductivities of 0.77W/mK to 1.80 W/mK. Moisture effect on concrete was recorded for the lightweight concrete as the thermal conductivity value reduced from 1.80W/m.K to 1.32W/m.K for the oven-dried concrete sample over a 1.5% (by weight) reduction in water content. The performance evaluation of the locally fabricated GHP apparatus showed a 3.03% percentage difference over ASHRAE's published data on oven-baked concrete thermal conductivities

Keywords- Building materials, Guarded hot plate, Steady State, Thermal Conductivity

1 Introduction

The concerns for energy reduction have increased the interest in the use of building materials with lower embodied energy to develop sustainable buildings (Marut et al., 2020). These materials such as cob, rammed earth, straw, mud, and laterite have an added advantage of widespread availability and lower cost than the conventional materials (Ali et al., 2020; Ogunsote, 1993). The use of these environmentally friendly building materials comes with the challenge of determining some of the thermo-physical properties of the materials required for building energy calculations (Isa et al., 2018).

Thermal conductivity of materials used in building construction is a property of primary interest to engineers in building energy and cooling/heating load calculations. Improper selection of thermal conductivity values leading to faulty designs of buildings and equipment negatively affects health and comfort of building occupants, and also impacts on overall building energy cost (Wakeham and Assael, 1999; Johra, 2021).

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The measurement of thermal conductivity is carried out under steady-state and transient conditions (Dubois and Lebeau, 2013), covering methods for electrically conducting materials like copper powders (Kusunose and Sekino, 2016; Bala et al.,1989) and poor conductors like building insulation material, using the Guarded Hot plate (GHP) technique. Xuan and Li (2000) used steady-state technique for heat transfer enhancement of Nano fluids. Rottmann et al. (2020) measured evacuated expanded perlite measured with guarded-hot-plate and transient-hot-wire method. The thermal conductivity measurement of poor conductors such as building insulation material, has been in existence, in various forms, since the late 1890s, whereas similar measurements on metals date back to at least the late 18th century (Revuelta et al., 2021).

The GHP technique has since become well established and recognized as a reliable method for measuring the thermal conductivity of poor conductors and is documented in standard C177-19 (ASTM, 2019). Its application for the measurement of thermal conductivity of insulation and building materials has become entrenched and widely used (Batool et al., 2018). A GHP, incorporating three-blocks-of-brass, was used by Raheem and Adesanya (2011) to study the thermal conductivity of Corn Cob Ash (CCA) blended cement mortar with a view to ascertaining its insulation characteristics. Their results indicated that with a 1:1 mix ratio; the thermal conductivity decreases from 1.80 W/m.K to 0.69 W/m.K when the CCA percentage replacement increases from 2% to 25% as against the control value of 2.40 W/m.K.

Not much works based on findings have been conducted using guarded hot plate apparatus for the measurement

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of local building materials. This paper presents the design and construction of a locally fabricated guarded hot plate and the performance evaluation with reference to results from ASHRAE's validated test equipment.

2 Materials and Methods

2.1 Materials

The sectional view of the Guarded hot plate apparatus (GHP) is shown in Figure 1. The GHP apparatus was designed to measure an expected range of thermal conductivity from ~0.001 W/mK up to~25 W/m.K**.**

2.2 Methods

A sectional view of the Guarded hot plate apparatus (GHP) is shown in Figure 1. This GHP apparatus was designed to measure an expected range of thermal conductivity from ~0.001 W/mK up to~25 W/mK**,** hence careful attention to details was ensured to achieve one-dimensional heat flow through the specimen.

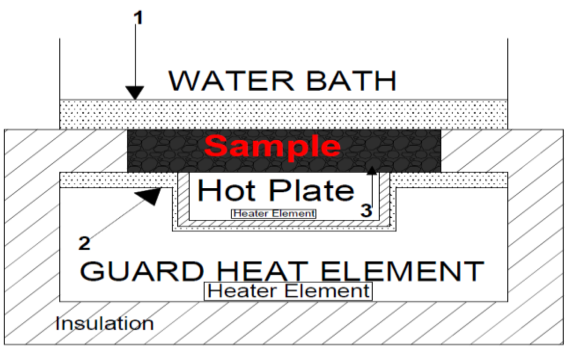

Fig. 1: Schematic diagram of the test apparatus (Labels- (1) Cold plate, (2) Guard heat element, (3) Hot plate)

2.2.1 The Hot Plate

Figure 2 shows the hot plate with a heater element embedded in it. The heater element terminal ends protrude through 10 mm diameter holes which are 80 mm apart. An Alternating current heater coil which has a capacity of 1000 W; 240V is embedded in the hot plate. Before placing the hot plate into the recess of the guard plate, a thermocouple was attached to the inner part of the hot plate for sensing the hot plate temperature.

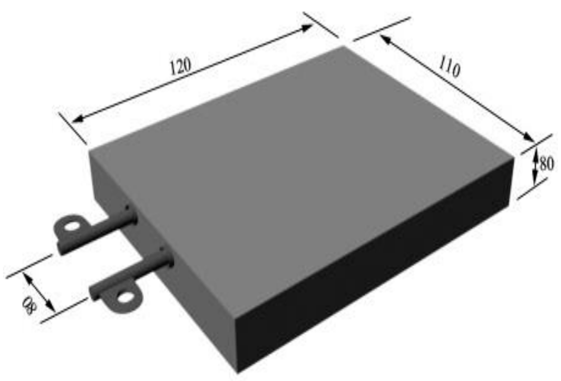

Fig. 2: Hot Plate with Embedded Heater Element

2.2.2 The Guard Plate

Figure 3 shows the sketch of the assembled guard plate. The guard plate prevents heat loss through the sides and bottom surface respectively. The guard plate is constructed of 6.35 mm aluminium and extends 47.5 mm beyond the hot plate. The hot plate fits into the recess created in the guard plate and are thermally separated by a 10 mm insulation-filled gap by the sides and below.

Another thermocouple of the same material as that in the hot plate is attached to the lower inner part of the guard plate to sense the guard temperature. The heating element (1000 W; 240V) is also fixed on the lower inner part of the guard plate but placed at 15 mm apart from the thermocouple. The assembled guard plate unit is then encased in a 50 mm thick Rockwool insulation. The process of fabrication covered marking out, cutting, folding, drilling, and joining.

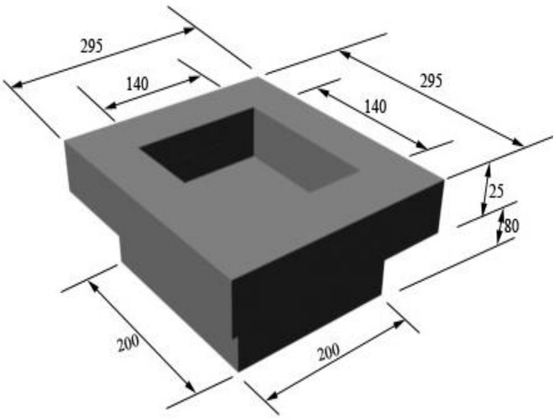

Fig. 3: Sketch of the assembled guard plate

2.2.3 The Cold Plate/ Ice Bath Assembly

Figure 4 is the sketch of the cold plate/ ice bath assembly. The ice bath which acts as heat sink rests on the sample. It is fabricated from a 6 mm thick square (290 mm × 290 mm) aluminium plate which is glued under the ice bath (290 × 290 × 140) mm with a thermally conductive epoxy which ensures that temperature measurements closely approximate the true temperature gradient across the plate.

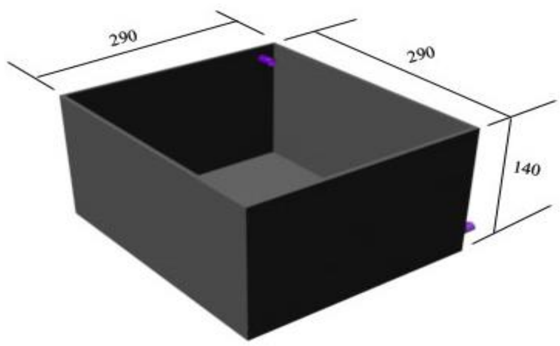

Fig. 4: 3-D sketch of the cold plate/ice bath assembly

2.2.4 The Apparatus Housing Assembly

This was made from a 2.0 mm mild steel sheet. It has 495 mm length by 300 mm width and has a height of 300 mm which extends only to 200 mm. The front plate measuring

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495 mm×155 mm has openings cut to exact sizes for the ammeter, voltmeter, light indicators and the on/off switch. The process of fabrication involved marking out, cutting, folding, drilling, arc welding, surface finish-grinding, filling, and painting.

2.2.5 Electrical Control System

The apparatus was designed and constructed with a separate compartment for the control and display instruments, and power supply unit. All wires for the meters, temperature sensors, and the power supply were connected to the terminal of the contactors via an on/off switch on the frame, which was then connected to the display instruments. Three digital temperature control meters with provisions for temperature resetting were linked to the thermocouples for reading the hot, guard, and cold plates' temperatures. The apparatus is equipped with a voltmeter and ammeter to measure and indicate the voltage and current to the plates. The power supply is routed through the contactors to the heater coils attached to the hot and guard plates respectively.

2.2.6 Power Requirements

The name-plate current for each of the heater elements for the hot and guard plate is 6 Amps at 220 Volts, and the apparent power is 1320 Watts while the active power is 1122 Watts.

2.3 Measurable Quantities

The quantities that need to be measured to enable the determination of thermal conductivity are the heat flux, thermal contact resistance, and material density.

2.3.1 Heat Flux

The average power, P_{av}, required for each of the samples to attain a steady-state temperature is given by equations (1) and (2) (Li *et al.*, 2012),

$$P_{av} = \frac{\sum \Delta P_i}{\sum \Delta t_i} \quad (1)$$

$$q_e = P = IV \quad (2)$$

The total time, $\sum \Delta t$, is incorporated in the virtual C++ programme was analysed to determine the thermal conductivity of the material at the desired temperature. The electrical power q_e is equal to the heat transfer of interest, q. But for ease of analysis, at steady state and constant heat flux $\ddot{q}$, q_e is assumed to be equal to the heat flux at a unit surface area (Morabito, 1989).

$$q_e = \ddot{q} = I \times V \times 0.8 \quad (3)$$

Where 0.8 is the Power factor, which accounts for the power loss in heater coils.

2.3.2 Thermal Contact Resistance

Thermal contact resistance R_c is given by equation (4) (Li et al., 2012),

$$R_c = \frac{1}{h_c} = \frac{\Delta T}{\dot{Q}/A} \quad (4)$$

Where h_c is the contact coefficient, ΔT is the temperature difference generated by the application of the measured heat input Q at the contact surface of area, A.

2.3.3 Thermal Conductivity Calculation

The thermal conductivity from Fourier heat conduction law is expressed by equation (5) (Raheem & Adesanya, 2011),

$$k = \ddot{q}_x \frac{L}{T_1 - T_2} \quad (5)$$

Where k =Thermal Conductivity of the material; $\ddot{q}_x$=Heat flux; L =thickness of specimen; T_1 = Temperature of hot plate; T_2 = Temperature of cold plate.

2.3.4 Density Measurement

The different densities of the samples were calculated from the measured mass and volume using equation (6),

$$\rho = \frac{m}{v} \quad (6)$$

Where ρ = Density, (kg/m^3); m = Mass, (kg); v = Volume, (m^3). The dimensions (length, width and thickness) of the sample were measured. The volumes of the samples were therefore determined using equation (7):

$$v = l \times w \times h \quad (7)$$

Where l = length (mm); w = width (mm); h = thickness (mm). Using equations (6 and 7), the density values were obtained.

2.4 Specimen Preparation

The preparation of the specimens involved two major processes: Formwork Production and Material Preparation.

2.4.1 Material Preparation

Apart from Cement, other materials namely, Laterite, Clay, and Sand were obtained in their raw state. The laterite materials were sourced from Budo Tuntun in Asa local government area of Kwara State, Nigeria. The initial preparation before moulding into slabs using the formwork involves breaking the freshly extracted earth, sifting the earth, and mixing the necessary amount of stabilizer with earth and water. This mix ratio used for the preparation is 1:2. Volume of water used in each sample preparation is 1240 mL. Cement (Portland cement) was added to bind the grains sand and particles of earth solidly together. The cement, sand and granite ratio of 1/2/4 was used. Salau (2008) referred to soil stabilization as the process of mixing additives with soil to improve its volume stability, strength, permeability and durability. Wet moulding was used for the samples and drying was done under cover for 14 days; the concrete was cured in a water trough within this period. Some of the moulded samples are shown in Plate 1. The results of the air-dry Weight measured are presented in Table 1

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Plate 1: Moulded test samples

Table 1. Air-Dry Weight of Samples

Samples	CC	L+C	L	S+C	CY+C
Air-Dry Weight (Kg)	5.022	3.036	3.733	5.140	3.439

Key: *Concrete =CC; Laterite =L; Cement =C; Sand =S; Clay = CY;*

2.4.2 Formwork Production

The formwork for this study is made from marine plywood. The surface of the plywood was treated to aid the production of samples whose surface will reduce contact resistances in the experiment. The formwork is designed to produce test samples of dimensions 195 mm × 190 mm × 55 mm.

2.5 Experimental Procedure

Each specimen was first placed on the hot plate within the measuring space of the apparatus, adjusted, and the cold plate-ice bath assembly placed above the sample. Sachets of frozen water were packed into the ice bath with mercury-in-glass inserted to measure the reference temperature. The starting set temperatures were entered, and the apparatus powered on through the on/off switch. The electrical power output to the hot plate and guard plate automatically cuts off once the set temperatures are attained. The temperatures of the hot plate, guard plate, and cold plates were recorded at intervals of 5 minutes. The temperature is carefully monitored until a steady state temperature is attained and the temperature is reset to a higher temperature value. The process is repeated at different temperature settings. Plate 2 shows a testing session of the GHP apparatus.

Plate 2: The designed and fabricated GHP Apparatus during a testing session

2.5.1 Thermal Conductivity Measurement

The thermal conductivities of each of the masonry building materials were determined by inputting the specimen thickness, L, temperature of the hot plate, T_1, and temperature of the cold plate, T_2, into the C++ program developed. The screen display on a computer for concrete is shown in figure 5.

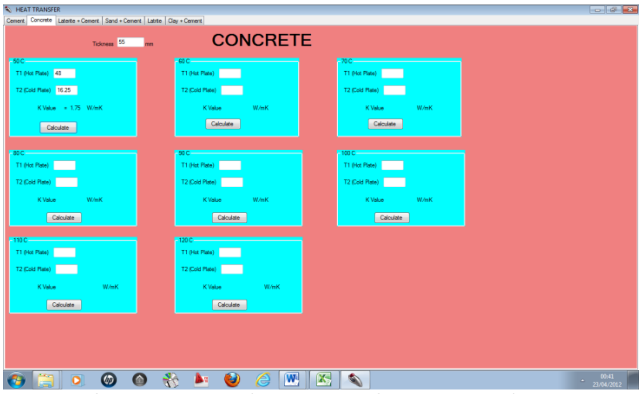

Fig. 5: Screen display of the Visual C++ Template for concrete thermal conductivity calculation

3 Results and Discussion

3.1 Thermo-Physical Measurements of the Samples

The thermal conductivity, air weight and density of the masonry samples were determined from measurements and analysis carried out as described in section 2. Thermal conductivity of the tested samples varied between a minimum of 0.77W/mK to a maximum of 1.80 Tables 2 – 4 indicate that the thermal conductivities increase with reducing temperature difference between the hot and cold plate temperatures.

Table 2. Thermal Conductivity of Oven Dried Concrete {Ratio: 1-2-4} at different Temperatures

Specimen Thickness (mm)	Hot Plate Temp (°C)	Cold Plate Temp (°C)	Thermal Conductivity (W/m. K)
55.00	52.0	14.0	1.25
55.00	50.0	14.0	1.32
55.00	48.0	14.0	1.36

Table 3. Thermal Conductivity of Laterite at different Temperatures

Specimen Thickness (mm)	Hot Plate Temp (°C)	Cold Plate Temp (°C)	Thermal Conductivity (W/m. K)
55.00	52.0	14.5	0.77
55.00	50.0	14.5	0.93
55.00	48.0	14.0	1.06

The effect of moisture content on thermal conductivity was observed as the thermal conductivity values reduced from 1.80W/m.K to 1.32W/m.K for the oven-dried concrete sample over a 1.5% (by weight) reduction in water content as shown in Table 4.

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Table 4. Samples Thermal Conductivity Values with Density

Samples	Air-dry Weight (Kg)	Density (Kg/m³)	Thermal Conductivities, ***k***, (W/m. K) at hot plate temperature (50°C)
Concrete	5.025	2461.16	1.80
Concrete (Oven Dried)	4.945	2423.43	1.32
Laterite + Cement	3.036	1487.87	1.28
Laterite	3.733	1829.45	0.93
Sand + Cement	5.140	2518.90	1.63
Clay + Cement	3.733	1829.45	0.35

Table 4 also shows the relationship between thermal conductivity and density of the different samples. Thermal conductivity increases with density in most solid materials. Sand and Cement mixture (Ratio 2:1) with a density of 2518.90kg/m³ has a thermal conductivity value of 1.63W/m. K when compared with Laterite having a thermal conductivity of 0.93W/m. K with a density value of 1829.45kg/m³.

3.2 GHP Hot and Cold Plate Temperatures

Figures 6 and 7 show the relationship between the hot plate and cold plate temperatures over time for the different test materials. The steady state temperatures were attained when the temperature difference was constant with time. In particular, the cold plates maintained uniform temperatures in all the tested cases as shown in figures 6 and 7. This was achieved through the use of the ice bath. The cold plate ensured a uniform heat dissipation which reduces transient temperature fluctuations that tend to add uncertainty to the measured thermal conductivity. The guarded edges ensured the heat flux from the hot plate passes through the specimens with minimal heat dissipation.

The hot plate effect on temperature results for the mixture of laterite and cement shows a steeper response to heat flux than the laterite only, which can be attributed to the material properties of cement. The addition of laterite to cement lowers its thermal conductivity.

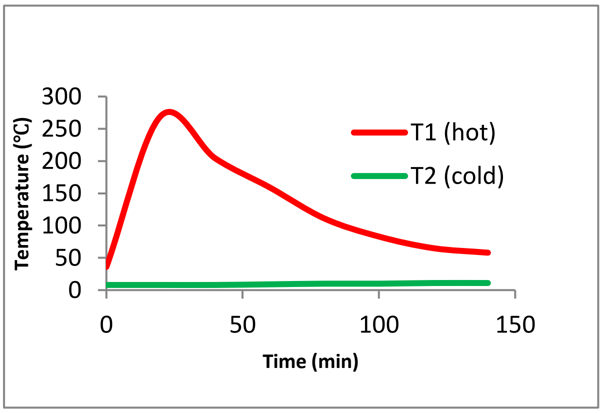

Fig. 6: Temperature of hot and cold plates vs. time for laterite

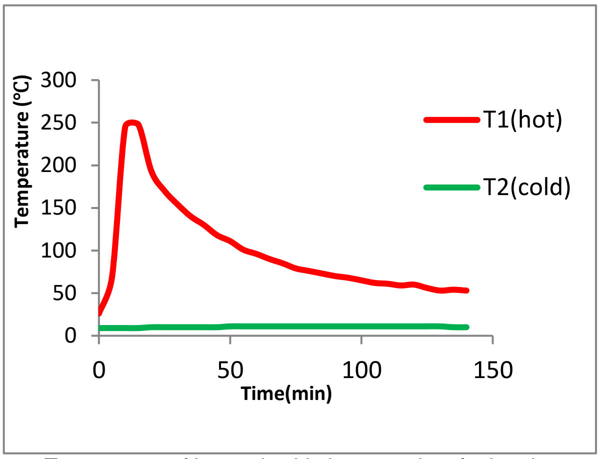

Fig. 7: Temperature of hot and cold plates vs. time for laterite + cement mixture

4 Performance Evaluation

Performance evaluation of the designed GHP equipment in characterizing the thermal heat conductivity of concrete was made. Performance of the locally constructed GHP Apparatus was compared with ASHRAE Standard Reference Material (Concrete-1:2:4) Test results obtained with an equivalent validated GHP apparatus (Szoke et al., 2014). Concrete was selected as a representative sample for the performance evaluation due to the wide availability of data on various mix- ratios of varying densities in literature (Sulaiman *et al*., 2022; Revuelta *et al*., 2021; Szoke *et al*.; 2014 Neville, 2012).

Table 5. Performance evaluation with the concrete sample

Material	Thermal Conductivity (W/mK)		Percentage difference(%)
	ASHRAE GHP	Locally Produced GHP	
Concrete (Air Dried)		1.80	
Concrete (Oven Dried)	1.28	1.32	3.03

The results from ASHRAE indicate a thermal conductivity value of 1.28 W/m. K. From Table 5, there is a 3.03% percentage difference above ASHRAE's result. According to Valore (1988) concrete has a very wide range of variation of specific heat: 600-1500 J/ kg K and thermal conductivity: 0.8 to 1.8 W/ m. K, depending on the composition (density) and water content of the concrete used.

5 Conclusions

The GHP apparatus was designed and fabricated to measure the thermal conductivity of some masonry building material. The materials measured include a varying mixture of sand, laterite, clay, granite with cement. Results for these materials covered a range of thermal conductivities of 0.77W/mK to 1.80 W/mK. for specimen sizes and hot plate temperatures below 60 mm and 300°C respectively.

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Further testing with the apparatus showed results for an oven-dried concrete falling within 5% of published (ASHRAE) values for ≤ 50°C. Lower thermal conductivity values were recorded for the specimens as their moisture content decreases, the thermal conductivity increases with moisture content. The thermal conductivity value for the Lightweight concrete sample reduced from 1.80W/m.K to 1.32W/m.K when oven-dried. This fabricated GHP has the added advantage of having a dual system cold plate which can be operated through either as an ice bath or water circulation pipe. The ice bath operation makes the equipment portable and can be used in any space where the room temperature can be controlled. The performance of the GHP test apparatus could further be improved by automating the ambient temperature monitoring through sensors, data extraction software and USB interface for data logging capability.

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