Journal of Casting & Materials Engineering Vol. 6 No. 2 (2022) 45–57
https://doi.org/10.7494/jcme.2022.6.2.45

A Simulation and Experimental Investigation of the Thermal Characteristics of Refractory Bricks Produced Using Fireclay and Agroforestry Wastes

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Received: 20 October 2021/Accepted: 27 April 2022/Published online: 28 May 2022.

Abstract

Manufacturing and processing industries usually consume large quantities of materials and energy in the course of their operations. The energy supplied for high-temperature processes are used partially for the actual technical process and between 30 to 40% of the energy escapes through the walls of the reactor into the atmosphere, leading to a high degree of thermal inefficiency and fuel consumption. This paper studies the thermal behaviour of insulating refractory bricks produced from a blend of fireclay and agroforestry wastes. The fireclays used were obtained from Ukpor deposit in Anambra State (Latitude 5.95°N, Longitude 6.92°E), Osiele deposit in Abeokuta, Ogun State (Latitude 7.18°N, Longitude 3.45°E) and Kankara Katsina State (Latitude 11.93°N, Longitude 7.41°E), all of which are in Nigeria. Samples were prepared with various weight percentages (60–100 wt.%) clays and (0–40 wt.%) of agroforestry waste, with grain sizes between 212 and 600 μm. Raw materials and the developed refractory bricks were characterised using appropriate standard techniques. The chemical, mineralogical constituents and phases present in the microstructure were examined. Physical and thermo-mechanical properties were investigated. The insulating refractory bricks developed have porosity of 78.83% , cold crushing strength (CCS) 3.144 kN/m^2 and thermal conductivity 0.04–0.046 W/(m·K) that compare favourably with imported bricks 75–85%, 2.756 kN/m^2 and 0.049 W/(m·K) in both physical, mechanical and thermal properties respectively. The reason is that the agroforestry waste used (coconut shell), served to create the pores that improve insulation after burning. Also the ash that remains serves as reinforcement to improve the mechanical properties. The thermal behaviour of the bricks was studied using Finite Element Method and shows a strong correlation with the experimental findings. This indicates that the produced insulating bricks have the thermal properties required for insulation of furnaces.

Keywords:
simulation, insulating bricks, microstructure, thermal characteristics

1. INTRODUCTION

Refractories are materials, which have high temperature and chemical resistance and are used in the insulation of furnaces and kilns against heat loss and chemical damage [1]. Refractory materials retain their shape, strength and chemical identity at high temperature. Refractory bricks play a very important role in the manufacturing industry mainly in the lining of furnaces, kilns, fireboxes and fireplaces. They can be inorganic, non-metallic in nature and depending on how porous they are, can be classified into two categories; dense and porous (insulating) refractories [2]. Insulating refractory bricks also known as porous refractory bricks are usually light in weight, low in thermal conductivity and resistant to high temperature [3].

In developing countries, most refractory bricks are imported and this adversely affects production rate and the cost of the final product. Studies are ongoing on the production of insulating refractory bricks with different combustible materials obtained locally to establish the right proportion to conform to international standards for insulating bricks. An earlier investigation by [4] on the use of coconut shell particulate to enhance the insulating refractory properties of Ukpor, Osiele and Kankara fireclays in Nigeria, showed that clays with 25–30% coconut shell and grain sizes of 212–300 μm fired at 1150–1200°C possessed enhanced physical, mechanical and insulating properties. Also, [5] investigated the effects of coal ash on some of refractory properties of Kankara clay, which has a low refractoriness, thermal resistance and high apparent porosity that are not satisfactory in refractory application. Medium duty fireclay brick capable of possessing good thermal shock resistance was made with the blend at 25 wt.% coal-ash as all the value obtained were within the recommended values for fireclay bricks. In [6], authors evaluated the performance of refractory bricks produced from some local clay deposits in Delta State, Nigeria. After being processed, the clay samples were tested for shrinkage, bulk density, cold compression strength and thermal shock resistance. The results show that the kaolin deposit at Oghara was found to be the best material suitable for the lining of the walls of most high thermally operated equipment as its fusion temperature is above the operating temperature of 1200°C. In [2], authors researched on the effects of sintering temperature and agro-wastes on the properties of insulation bricks. In this research, kaolin, ball clay, sawdust and rice husk were used to produce insulation bricks through the solid-state synthesis method. It was found that as the amounts of kaolin used in preparing the samples decreased, the bulk density, modulus of rupture and cold crushing strength (CCS) of the bricks decreased while the water absorption capacity and linear shrinkage increased. The temperature of sintering slightly affected the physical and mechanical properties of the insulation bricks. The samples that were sintered at 1200°C had slightly better properties compared to those sintered at 1100°C.

The need for insulating bricks cannot be over emphasized as several high temperature operations are still ongoing. It has been observed that 30 to 40% of the energy supplied for this operation escapes through the walls into the atmosphere resulting to thermal inefficiency and high fuel consumption [7]. In this research, the thermal characteristics of insulating refractory bricks produced from fireclay and agroforestry waste will be investigated. This is to improve furnace thermal efficiency and thereby reduce high fuel consumption and the cost of production. The aim of this study is to produce refractory bricks with high insulating properties using clays from Nigeria and agroforestry wastes.

2. MATERIALS AND METHODS

2.1. Sample preparation

The materials used for this research are: agroforestry waste (coconut shell) and fireclays collected from Ukpor deposits in Anambra State (Latitude 5.95°N, Longitude 6.92°E), Osiele in Ogun State (Latitude 7.18°N, Longitude 3.45°E) and Kankara Katsina State (Latitude 11.93°N, Longitude 7.41°E), all in Nigeria. The clays used for this study were collected from a depth of 3 meters down the threshold and 6 meters interval using a digger and shovels. The coconut shell (CS), meanwhile, was collected from a coconut chips factory at Ibadan, Nigeria.

The chemical analyses of the as-received materials were conducted using Atomic Absorption Spectrometer (AAS) Perklin Elmer Analyst 200 model at the Chemistry Department, University of Lagos.

The clay and coconut shells were washed, sun dried, crushed with a jaw crusher and ground to finer particles using a ball milling machine at the Federal Institute of Industrial Research, Oshodi (FIIRO). The pulverized materials were sieved using a sieve aperture of 212–500 μm. The sieves were selected after a trial-test. The raw materials were weighed using a METTLER PJ 300 digital weighing machine. Various samples comprising (60–100 wt.%) clays and (0–40 wt.%) of agroforestry waste were produced by mixing clay and agroforestry waste with 40–60 ml of water as shown in Table 1.

Table 1
Mix formulations of the materials (clay and agroforestry waste)

Sample No.	Clays [wt.%]	Agroforestry waste [wt.%]	Clay weight [g]	Agroforestry waste weight [g]
1(Control)	100	0	1000	0
2	95	5	950	50
3	90	10	900	100
4	85	15	850	150
5	80	20	800	200
6	75	25	750	250
7	70	30	700	300
8	65	35	650	350
9	60	40	600	400

The mix formulation was determined through trial-tests. The mould contains a maximum of 1000 g of clay at a time. That was the reason behind using 1000 g for calculating mix formulation.

The compaction was conducted after mixing, in cleaned and oil lubricated moulds of different shapes and sizes (76.2 × 76.2 × 76.2 mm^3, 60 × 60 × 15 mm^3, 50 × 75 mm^2, 95 × 45 × 12 mm^3 and 220 × 110 × 65 mm^3 for CCS, porosity, thermal shock resistance, linear shrinkage tests and for standard bricks respectively).

Various tests were carried on the produced samples.

2.2. Sample characterisation

2.2.1. Physical properties

Bulk density: The bulk density test was carried out by measuring the dry weight of the samples (R) before soaking the samples in hot water for 3 hours and measuring the weight (S) after soaking. The suspended weight in water (W) was taken. Thereafter the value of the bulk density was calculated using Equation (1):

$$\text{Bulk density} = \frac{\rho \times R}{S - W} \tag{1}$$

Apparent porosity: The apparent porosity of the samples were measured according to [8] standard. The value was calculated using Equation (2):

$$\text{Apparent porosity} = \frac{S - R}{S - W} \times 100\% \tag{2}$$

2.2.2. Mechanical property

Cold crushing strength (CCS) is the amount of load that refractory material could withstand after it has been fired to a temperature of 1200°C. This was carried out in accordance with [9] standard, the value was calculated using Equation (3):

$$\text{Cold crushing strength} = \frac{\text{maximum load}}{\text{crossectional area}} \tag{3}$$

2.2.3. Thermal properties

Linear shrinkage: This was carried out in accordance with [10] standard. The value was calculated using Equation (4):

$$\text{Linear shrinkage} = \frac{(l_o - l_i)}{l_o} \times 100\% \tag{4}$$

where:

l_o – original length,
l_i – final length.

Thermal conductivity: The thermal conductivities of the samples were carried out in accordance with [11]. The test samples were measured using a KD2 Pro Thermal Properties Analyser at the Geology Laboratory, University of Ibadan, Nigeria.

Metallographic examination: The micro-structural examination of the samples was carried out using Scanning Electron Microscope (SEM), Zeiss model EVO10, at the Department of Mechanical Engineering Laboratory, the University of Ottawa, Canada.

2.3. Simulation of heat transfer in refractory bricks

The thermal behaviour of the developed brick was conducted using a Finite Element Modelling software (FlexPDE). The rate of heat transfer in the insulating brick was investigated using three bricks with different thermal conductivities.

The mesh grid of the nodes throughout the brick is shown in Figure 1.

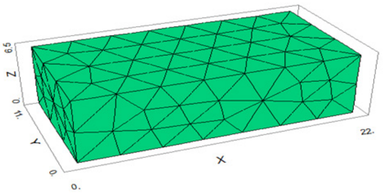

Fig. 1. Mesh grid of 934 nodes through the cross-section of the brick [cm]

The governing equation is given in Equation (5a) and (5b):

$$\frac{\rho C_p}{K_{eff}} \frac{\partial T}{\partial t} = \left[\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} \right] \tag{5a}$$

$$K_{eff} = (1 - \varepsilon) K_{solid} + \varepsilon K_{air} \tag{5b}$$

where:

$K_{\text{eff.}}$ – effective thermal conductivity,
K_{solid} – thermal conductivity of the solid,
K_{air} – thermal conductivity of the air,
ε – porosity,
C_p – specific heat capacity,
ρ – density of the brick,
T – temperature,
t – time.

The initial conditions inside the furnace were: when $t = 0$, then $T = T_\alpha$, where T_α is the ambient temperature.

Bundary conditions: At the boundary, $t > 0$, $x = 0$, $0 \le y \le B$ and $0 \le z \le H$ the equations explain what happened at each face of the brick during heat transfer; $x = 0$ shows at the beginning of x-axis i.e. in x direction. Also, at the boundary, heat conducted by the brick equals heat loss by convection this is expressed in Equation (6):

$$-K \frac{\partial T}{\partial x} = h_c (T - T_\alpha) \tag{6}$$

Heat conducted by the brick equals heat loss by convection.

At the end of *x*-axis: $t > 0$ (this is at the end of x-axis, when $x = L$), $x = L$, $0 \le y \le B$ and $0 \le z \le H$

where:

L – length of the brick,
B – breadth of the brick,
H – height of the brick,
K – thermal conductivity of the brick,
h_c – convection heat transfer coefficient.

Heat reaching the surface by conduction is equal to heat leaving the surface by convection to the space between two components due to thermal contact resistance this is expressed in the same way as shown in Equation (6).

At the beginning of *y*-axis: $y = 0$, $0 \le x \le L$, $0 \le z \le H$, then heat conducted by the brick equals heat loss by convection as expressed in Equation (7):

$$-K \frac{\partial T}{\partial y} = h'_c (T - T_\alpha) \tag{7}$$

where h' is the face inside the furnace.

At the end of *y*-axis: $t > 0$, $y = B$, $0 \le x \le L$, $0 \le z \le H$, then heat conducted by the brick equals heat loss by convection as expressed in Equation (8):

$$-K \frac{\partial T}{\partial y} = h_c (T - T_\alpha) \tag{8}$$

At the beginning of *z*-axis: $z = 0$, $0 \le x \le L$, $0 \le y \le B$ and the heating element was inserted at this face, then: the quantity of heat from the heating element equals the quantity of heat conducted by the brick as shown in Equation (9):

$$-K \frac{\partial T}{\partial z} = Q'' \tag{9}$$

where Q'' is the quantity of heat from the heating element.

At the end of *z*-axis: $t > 0$, $z = H$, $0 \le x \le L$, $0 \le y \le B$, also the quantity of heat from the heating element equals the quantity of heat conducted by the brick (see Equation (10)).

$$-K \frac{\partial T}{\partial z} = Q'' \tag{10}$$

Table 2
Chemical composition of clay and selected agroforestry waste

Raw materials	Compound [%]									
	Al_2O_3	SiO_2	Fe_2O_3	MgO	CaO	Na_2O	K_2O	TiO_2	H_2O	LOI
Ukpor clay (U)	27.79	53.73	1.24	0.87	0.01	0.56	2.10	0.52	0.003	13.16
Osiele clay (O)	36.23	45.31	0.12	0.52	0.16	0.05	0.04	0.07	0.002	13.06
Kankara clay (K)	25.72	58.84	0.86	0.69	0.24	0.56	1.44	0.34	0.002	7.15
Coconut shell (C)	1.92	2.46	0.24	0.11	0.15	0.20	0.13	0.02	0.001	93.47

3. RESULTS AND DISCUSSION

3.1. Chemical composition

The result of the chemical composition analyses shown in Table 2 indicates that the major constituent of agroforestry waste is organic matter, as captured in the high loss on ignition (LOI) values for the sample. Due to the fact that it is volatile at high temperatures, it is collected as LOI therefore, the agroforestry waste is a carbonaceous material. This can be attributed to the high loss on ignition (LOI) of 93.47% observed in the result. Silica, is also prominent in the waste being the parameter with the highest inorganic content, in the agroforestry waste. It is also the major constituent in the clay which serve as a matrix material. The clay also contains high percentage of alumina, which increases its refractoriness.

3.2. Bulk density

The bulk density values of the samples as a function of the agroforestry waste content are shown in Figure 2. As the amount of waste increased, the density value decreased almost linearly. This property is affected by factors such as nature of the materials blended in the clay sample, particle size, etc. [12]. The nature of materials implies increase in the amount of organic matter present, which leaves air spaces during sintering thereby resulting to decrease in the bulk density values.

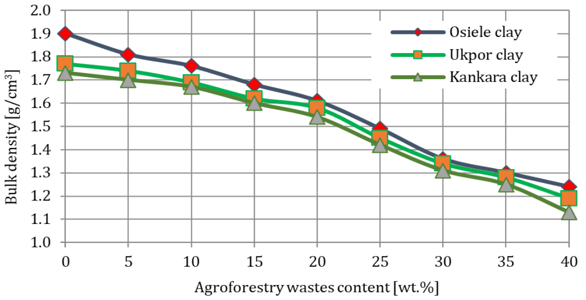

Fig. 2. Variation of bulk density with agroforestry wastes content

3.3. Apparent porosity

The result of apparent porosity is presented in Figure 3. It is observed that as from 25 to 30 wt.% of waste (Fig. 3), there is a sharp increase in porosity followed by a relatively steady portion when compared to the portion below 25 wt.%, this indicates the reasonable amount of agroforestry wastes required. The results obtained show that as the percentage of the waste increases (from 0 to 40 %), the porosity of the samples increases (from 20.07 to 88.09 %, for Osiele clay), (from 31.22 to 89.36 %, for Ukpor clay) and (from 34.10 to 91% for Kankara clay). This can be attributed to the high loss on ignition of the agroforestry wastes, which create void spaces (Tab. 1). This implies that the waste consists of a high amount of combustible material itself, an indication of high porosity. The agroforestry wastes burn off on sintering thereby creating pores, this is in conformity with [12]. The same trend is observed in (Fig. 3). An increase in the grain sizes of the waste, leads to an increase in the porosity of the samples. The values of apparent porosity for the insulating refractory brick samples above 25 wt.% of agroforestry wastes fall within the range of values (75–85%) for insulating bricks according to [8]. This implies that agroforestry waste can be used to improve the insulating properties of clay bricks.

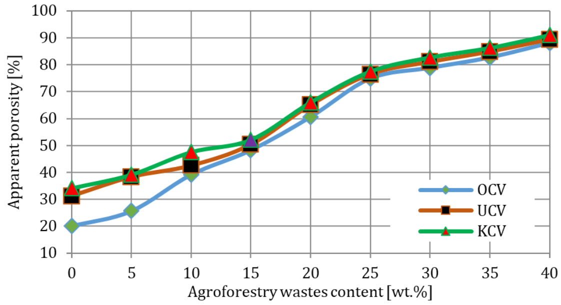

Fig. 3. Variation of apparent porosity of bricks with agroforestry wastes content at 1150°C

Figure 4 shows that thermal conductivity decreases with increase in the weight percentage of the agroforestry wastes. This is attributable to the increase in the formation of pores that hinder heat transfer from one particle to another.

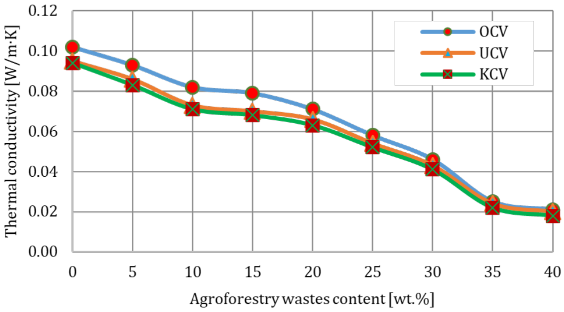

Fig. 4. Variation of thermal conductivity with agroforestry wastes content

Micrographs in Figures 5 and 6 clarify the result by revealing that the pores in the bricks increase with a rise in agroforestry wastes content. When there is an increase in porosity, entrapped air between the particles inhibits the rate of heat transfer leading to a reduction in thermal conductivity [13].

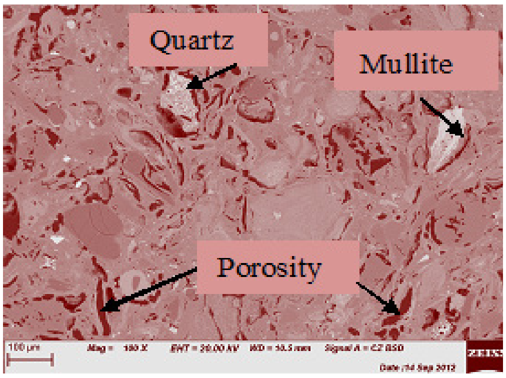

Fig. 5. OT4 (no additive) fired at 1150°C, scale: 100 μm

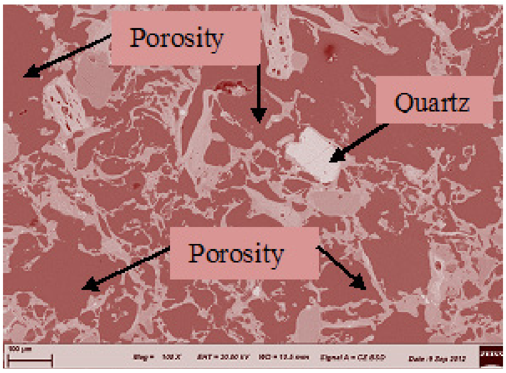

Fig. 6. 1OCXT4 (40% additive) fired at 1150°C, scale: 100 μm

3.4. Cold crushing strength (CCS)

Figure 7 reveals a slight increase in CCS of bricks fired at 950–1000°C due to partial bonding.

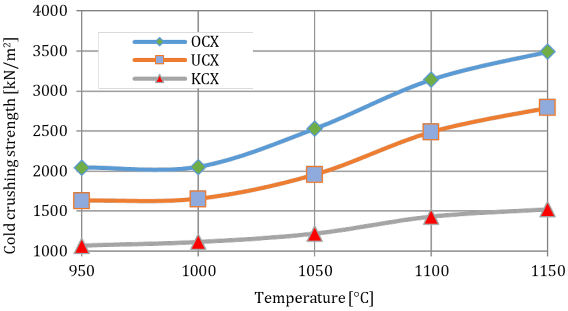

Fig. 7. Variation of CCS with firing temperature of bricks with 30% agrowaste

Between 1000–1100°C, there is a sharp increase in the CCS, which indicates the range of temperature at which considerable bonding occurs between the particles to form a strong coherent body. Meanwhile at a temperature of 1140°C, the increase in CCS tends to be reduced. This is as a result of vitrification that has taken place, during the glassy phase. The degree of variation observed in Figure 7, especially between bricks of Kankara clay and the other clays is as a result of difference in geological history (compositions) of the clays. The CCS of the developed bricks with an admixture of coconut shell and Osiele clay (OCX) as well as Ukpor clay and coconut shell (UCX) are within [9] standards. Bricks produced from Kankara clay, however, have lower strength compared to Osiele and Ukpor clays.

3.5. Simulation of heat transfer in the bricks

Three bricks with thermal conductivities of 0.102 W/(m·K), 0.046 W/(m·K) and 0.049 W/(m·K) and density (ρ) of 2.16, 1.36 and 1.30 g/cm^3 respectively were used. These represent the dense (control) brick without additive (100% clay), the domestically developed porous brick with 30 wt.% of agrowaste and an imported porous brick respectively.

Assumptions made include:

- the thermal properties of the brick are assumed to be constant,
- the brick is to be assumed isotropic,
- the mode of heat transfer in the brick is dominated by heat conduction,
- there is no internal heat generation in the brick.

The heat generated from the heating element installed round the bricks in the furnace are transferred starting from the edges to the core of the bricks as shown in Figure 8.

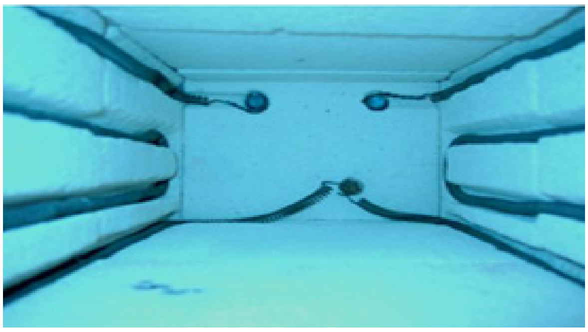

Fig. 8. Installation of heating elements round the bricks

The results of the simulation which revealed the thermal distribution in the bricks at different times are shown in Figures 9–16.

The thermal behaviour of imported porous bricks are similar to that of domestically produced porous bricks containing 30 wt.% of wastes. It takes 9 hours to attain a steady state in the two bricks (Fig. 16a and 16b). But for the domestically produced bricks without any additive (control), it takes only 4 hours (Fig. 14a) to attain a steady state. This confirms that the porous bricks insulate more than the dense bricks due to the large number of pores present in the insulating bricks.

In addition, the longer time to attain a steady state implies low rate of heat transfer, which indicates the high thermal resistance of the porous bricks, thus a reduction in the rate of heat loss through the bricks when installed at the walls of the furnace.

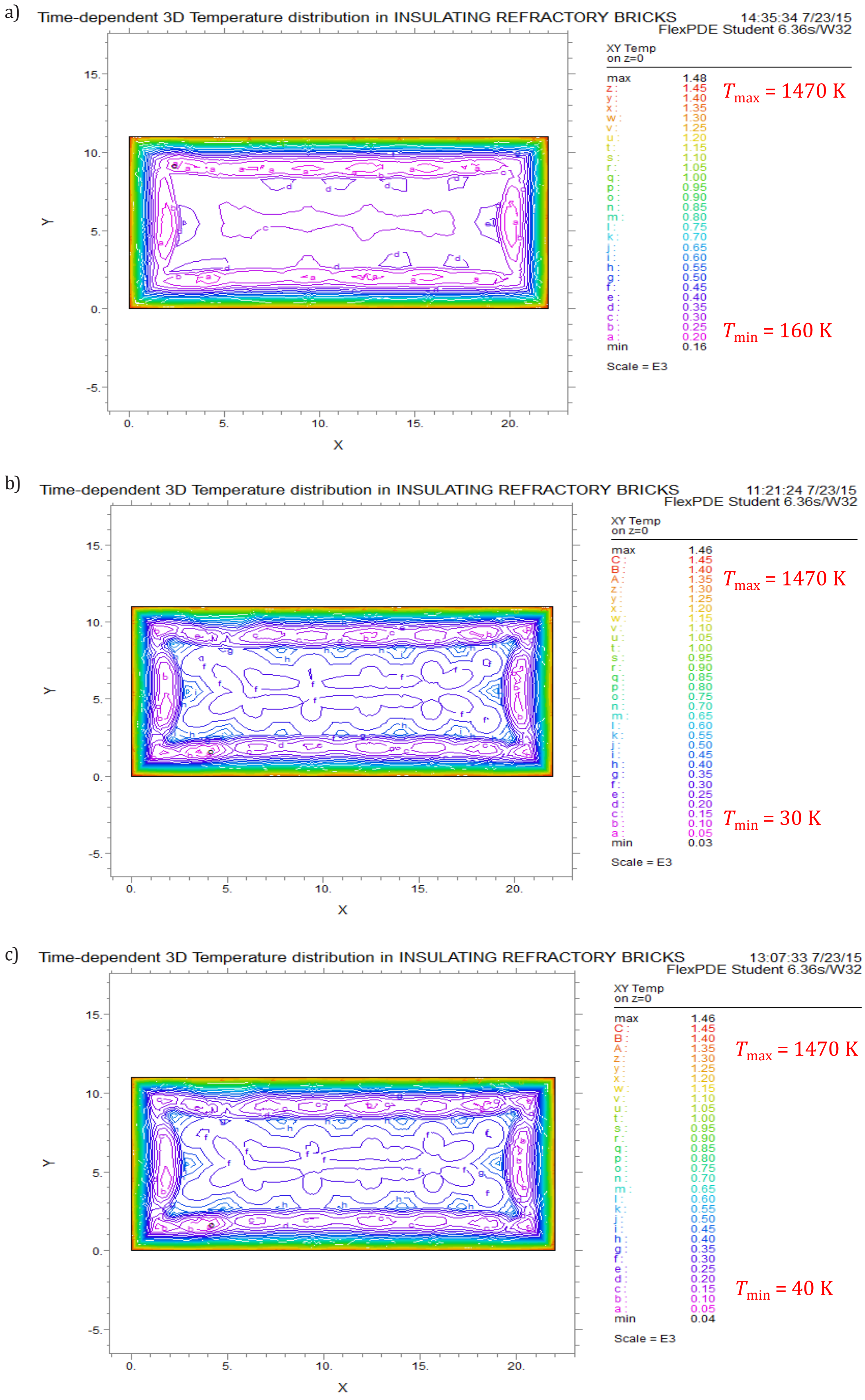

Fig. 9. Graph of heat transfer: a) in brick of 100% clay with K = 0.102 W/(m·K) at 60 s; b) in domestic porous brick with K = 0.046 W/(m·K) at 60 s; c) in imported porous brick with K = 0.049 W/(m·K) at 60 s

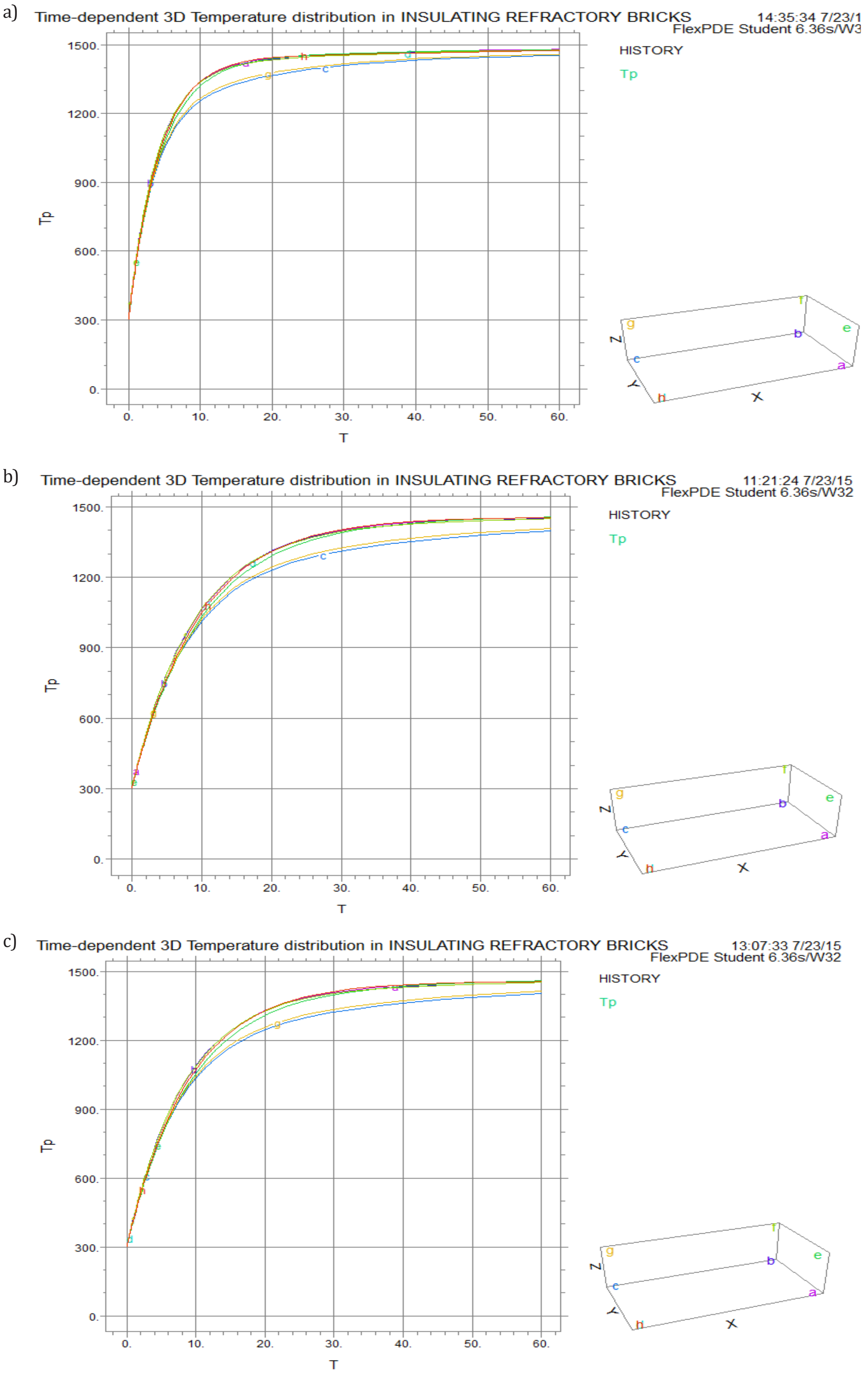

Fig. 10. Graph of heat transfer: a) in domestic dense brick (control) at 60 s; b) in domestic brick with $K = 0.046$ W/(m·K) at 60 s; c) in imported porous brick at 60 s

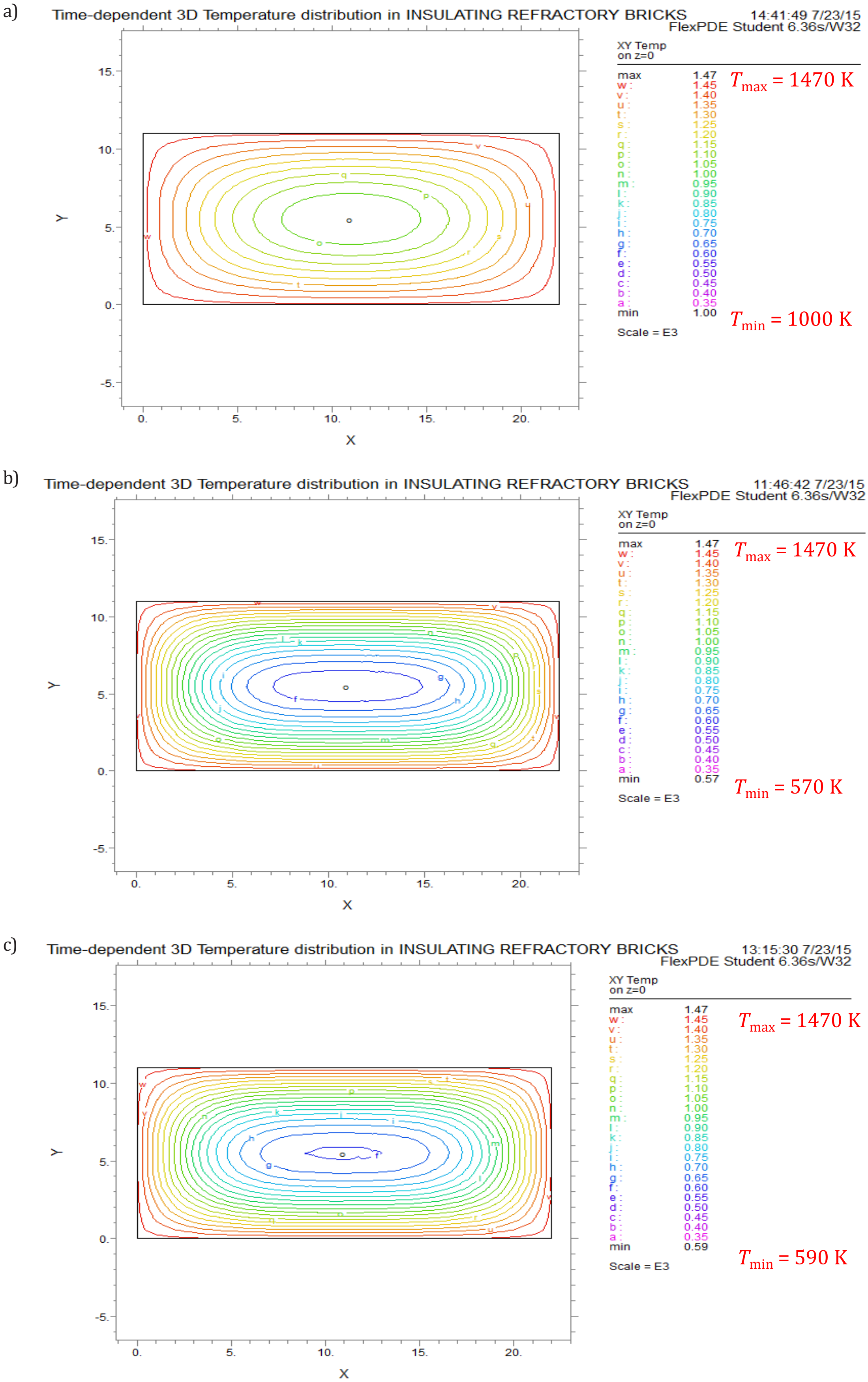

Fig. 11. Graph of heat transfer: a) in domestic dense brick (control) with K = 0.102 W/(m·K) at 1 h; b) in domestic porous brick with K = 0.046 W/(m·K) at 1 h; c) in imported porous brick with K = 0.049 W/(m·K) at 1 h

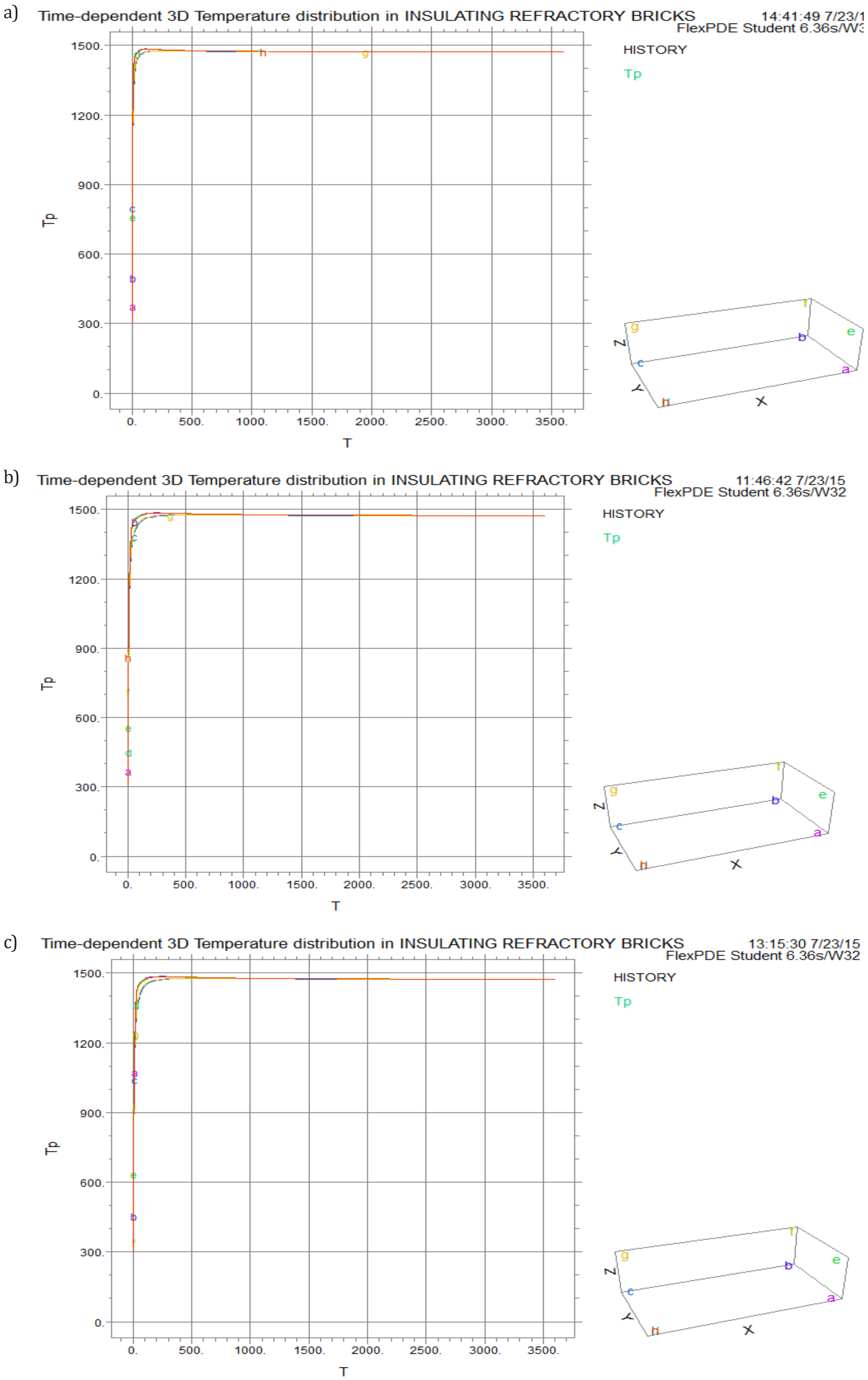

Fig. 12. Graph of heat transfer: a) in domestic dense brick (control) at 1 h; b) in domestic porous brick with K = 0.046 W/(m·K) at 1 h; c) in imported porous brick with K = 0.049 W/(m·K) at 1 h

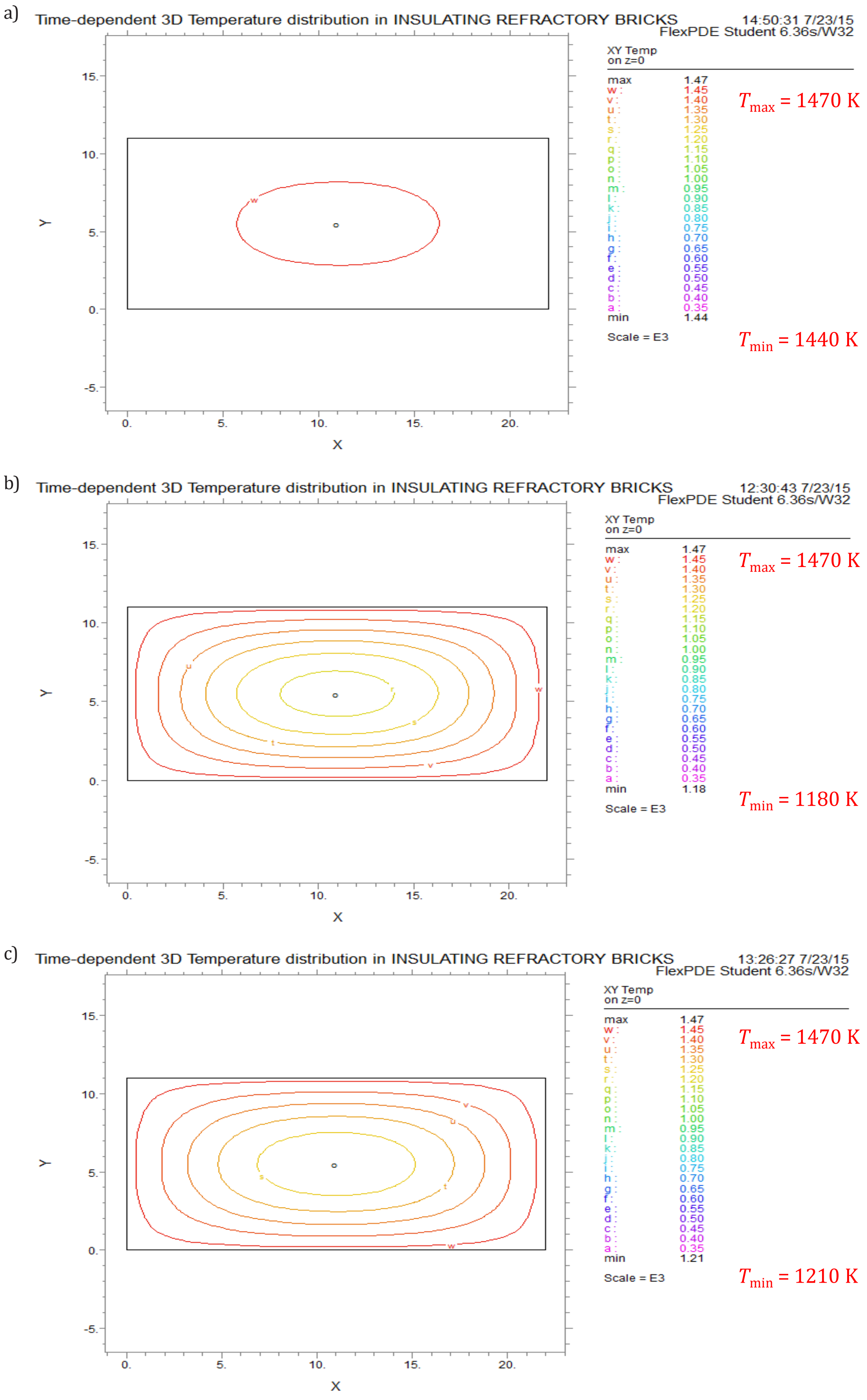

Fig. 13. Heat transfer: a) in domestic dense brick (control) with $K = 0.102$ W/(m·K) at 3 h; b) in domestic porous brick with $K = 0.046$ W/(m·K) at 3 h; c) in imported porous brick with $K = 0.049$ W/(m·K) at 3 h

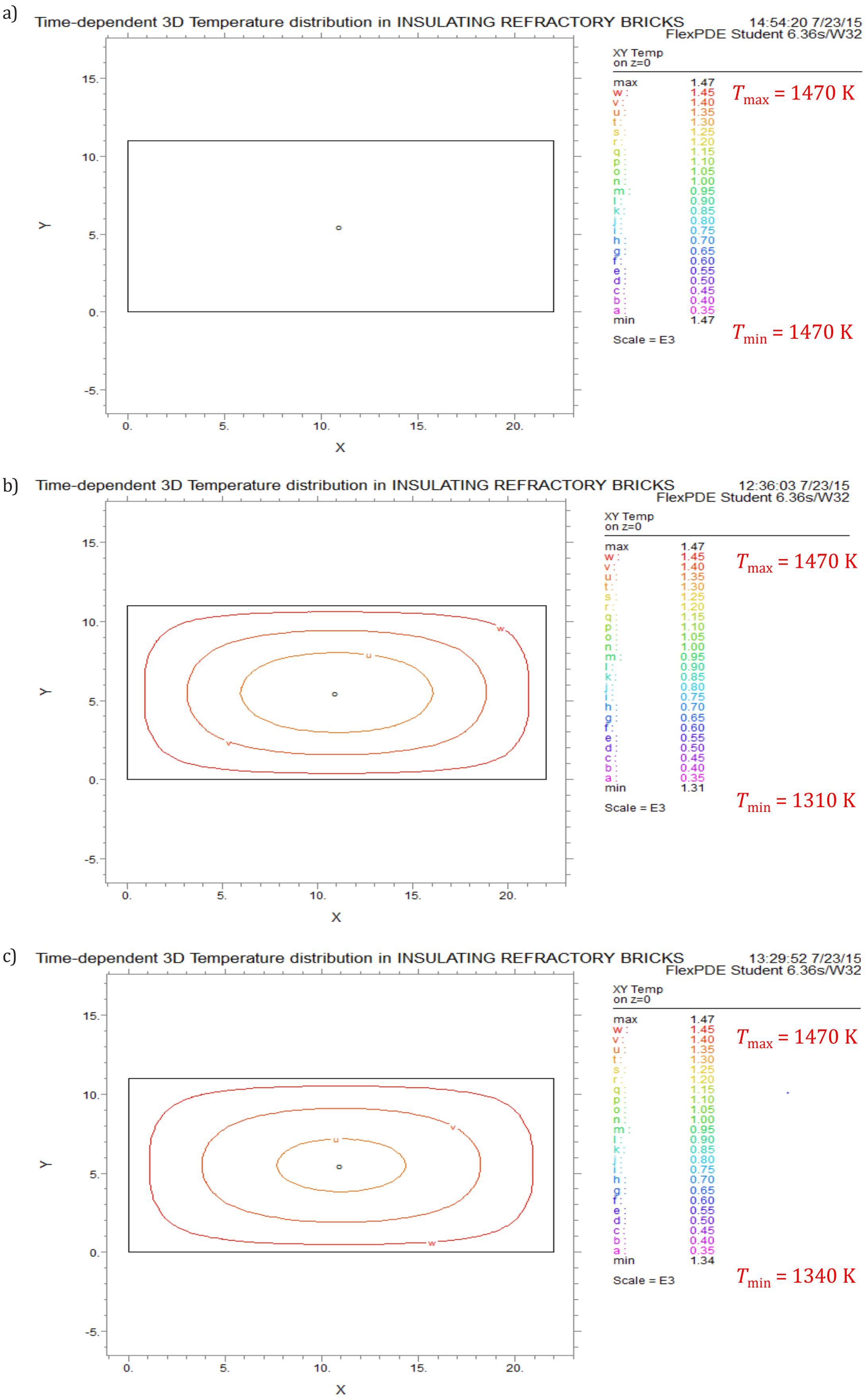

Fig. 14. Heat transfer: a) in dense brick (control) with $K = 0.102$ W/(m·K) at 4 h; b) in domestic porous brick with $K = 0.046$ W/(m·K) at 4 h; c) in imported porous brick with $K = 0.049$ W/(m·K) at 4 h

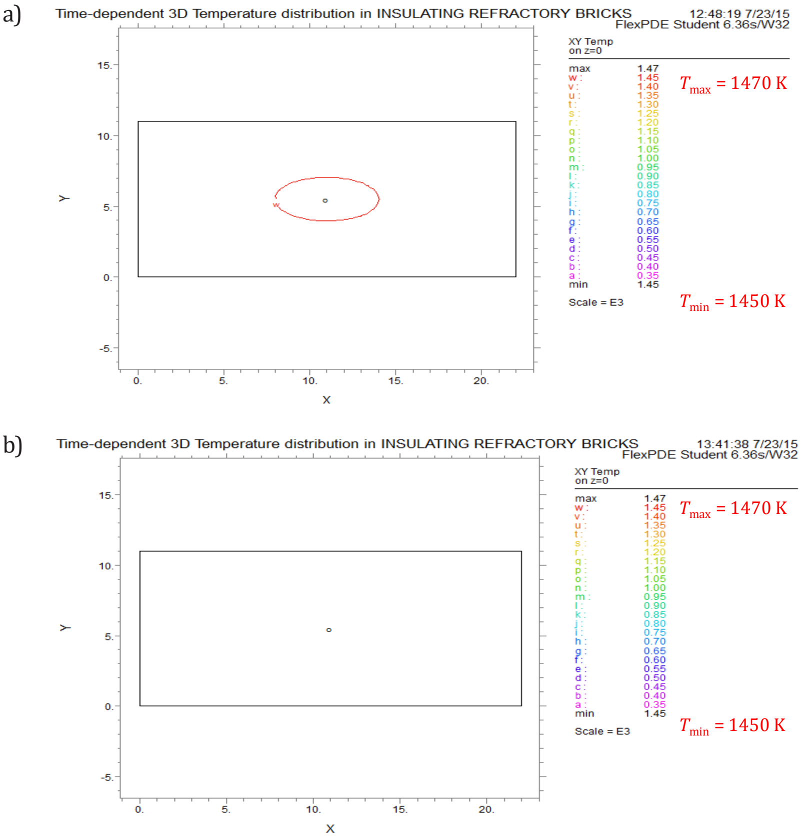

Fig. 15. Heat transfer: a) in domestic porous brick with $K = 0.046$ W/(m·K) at 7 h; b) in imported porous brick with $K = 0.049$ W/(m·K) at 7 h

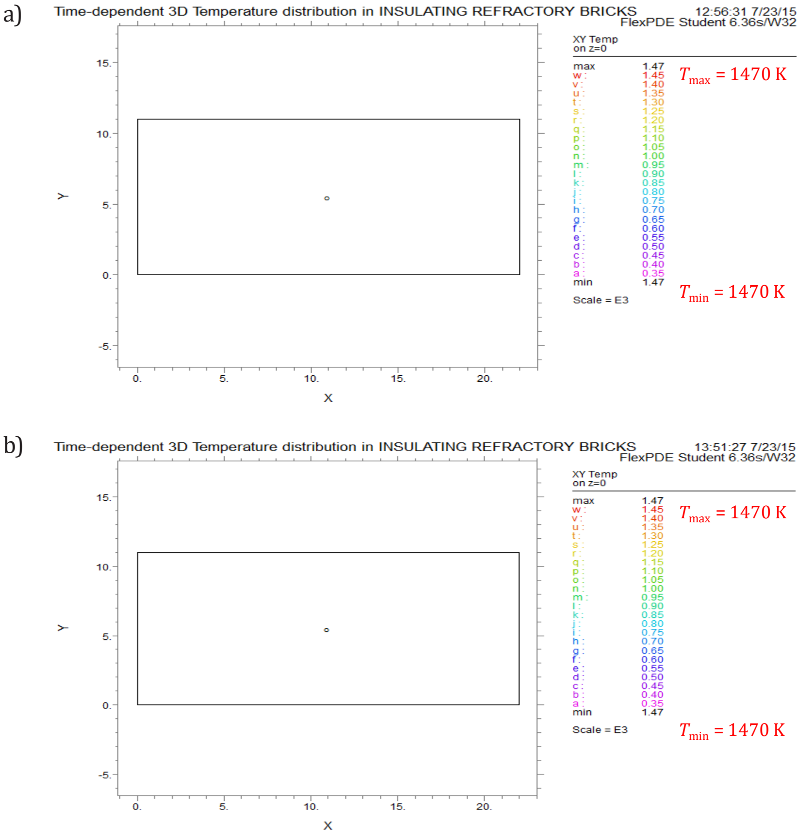

Fig. 16. Heat transfer: a) in domestic porous brick with $K = 0.046$ W/(m·K) at 9 h; b) in imported porous brick with $K = 0.049$ W/(m·K) at 9 h

Thus, agroforestry waste can be used to enhance the insulating properties of fireclays.

4. CONCLUSION

This research was carried out to experimentally investigate and simulate the thermal characteristics of refractory bricks produced using Nigerian fireclays and agroforestry wastes. Tests were carried out to study the physical, mechanical and thermal properties, as well as microstructural examinations and simulations.

It can be concluded from the results obtained that, the domestically developed insulating refractory bricks in terms of porosity (78.83%), CCS (3.144 kN/m^2) and thermal conductivity (0.041–0.046 W/(m·K)) compare favourably with imported bricks (75–85%, 2.756 kN/m^2 and 0.049 W/(m·K)) in terms of their physical, mechanical and thermal properties. These values are within the ASTM standard specification of 0.023–0.25 W/(m·K).

In addition, the thermal behaviour of imported porous brick is similar to that of domestically produced porous brick with 30 wt.% of wastes. It takes 9 hours to attain steady state in the two bricks.

Thus, the domestically developed insulating bricks can be used as an alternative to expensive imported bricks in manufacturing and processing industries.

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